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16. ABSTRACT

This project has investigated several processes for the conversion of the organic fraction of municipal solid waste (MSW) to a powder. The study concentrated on two types of processes: (1) conversion of MSW to a powdered carbon char by low-temperature pyrolysis, and (2) embrittlement of cellulose waste by thermal-chemical treatment. This report describes the results of these studies.

The first phase of this project was devoted to identifying processes that offer a potential for enhanced product recovery, an evaluation of chemical treatments to improve carbon recovery from pyrolysis processes, an evaluation of laboratory processes for the production of gaseous and liquid fuels, and a laboratory investigation of embrittlement processes for cellulose wastes. The second phase of the program was concerned with further laboratory studies of the embrittlement process, pilot studies of the embrittlement process with shredded newsprint and refuse derived fuel, and an engineering and economic assessment for a plant to process powdered cellulose for use as fuel. A comprehensive description of PhaseI was presented in an earlier report entitled "Investigation of Advanced Thermal Concepts for Obtaining Improved MSW-Derived Products" (EPA-600/7-78-143). This report summarizes the results of Phase I and provides a comprehensive review of the work conducted in Phase II of the program.

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EPA-600/2-80-121
August 1980

OBTAINING IMPROVED PRODUCTS FROM THE ORGANIC FRACTION OF MUNICIPAL SOLID WASTE

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

This report presents information resulting from a study of chemical and thermal treatments to improve the quality of the products derived from the organic fraction of municipal solid waste. Processes for obtaining powdered fuels are described in depth. It is hoped that the information provided in this report will be of assistance to researchers and developers concerned with resource recovery endeavors.

Francis T. Mayo, Director
Municipal Environmental
Research Laboratory

ABSTRACT

Many systems have been developed for steam or fuel production from Municipal Solid Waste (MSW), but the quality and consistency of such fuels have not been completely satisfactory. As conventional fuels become more difficult to obtain, the need grows for processes that can produce MSW-derived fuels of higher quality and greater consistency.

One promising technology is for the production of powdered fuels from cellulose waste. This project has investigated several processes for the conversion of the organic fraction of MSW to a powder. The study concentrated on two types of processes: (1) conversion of MSW to a powdered carbon char by low-temperature pyrolysis, and (2) embrittlement of cellulose waste by thermal-chemical treatment. This report describes the results of these studies.

The first phase of the project was devoted to identifying processes that offer a potential for enhanced product recovery, an evaluation of chemical treatments to improve carbon recovery from pyrolysis processes, an evaluation of laboratory processes for the production of gaseous and liquid fuels, and a laboratory investigation of embrittlement processes for cellulose wastes. The second phase of the program was concerned with further laboratory studies of the embrittlement process, pilot studies of the embrittlement process with shredded newsprint and refuse-derived fuel, and an engineering and economic assessment for a plant to process powdered cellulose for use as a fuel. A comprehensive description of Phase I was presented in an earlier report entitled "Investigation of Advanced Thermal Chemical Concepts for Obtaining Improved MSW-Derived Products" (EPA-600/7-78-143). This report summarizes the results of Phase I and provides a comprehensive review of the work conducted in Phase II of the program.

This report was submitted in fulfillment of Grant No. R-804421-07 by the University of Dayton Research Institute under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period September 1, 1976 to January 1, 1979, and work was completed as of January 1, 1979.

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CONVERSIONS

Acres x 0.4 = hectares

Tons x 0.9 = metric tons

yd^3 x 0.76 = m^3

ft x 0.3 = m

ft^2 x 0.09 = m^2

ft^3 x 0.03 = m^3

in x 2.5 = cm

lb x 0.45 = kg

million BTU x 1.054 = mkj

gal x 3.8 = ℓ

qt x 0.95 = ℓ

oz x 28.0 = g

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SECTION 1

INTRODUCTION

The purpose of this study was to investigate the potential of known processes that could improve the quality of the fuels or other products derived from the organic fraction in refuse. Since cellulose products are the major constituents of the organic fraction in refuse, it seemed likely that a number of the processes employed in the pulp, paper, and textile industries would have considerable potential for refuse processing.

To accomplish effectively the stated objective for this study, a comprehensive review of processes for making refuse a better fuel was performed. Information was obtained from the open literature and through personal contacts. Possible processes for improving the quality of products from the organic fraction derived from municipal solid waste (MSW) were determined, and descriptions were developed for each process.

This study concentrated on those processes designed to produce a carbon char, a cellulose powder, and liquid and gaseous fuels from the MSW. The production of carbon char was carried out by the use of chemical treatments that promote char formation at lower pyrolysis temperatures. For the production of powdered cellulose, the chemical and thermal treatments that cause cellulose embrittlement were of most interest. For the production of gaseous and liquid fuels, two processes were evaluated -- the Worcester Polytechnic hydrogenation-liquefaction process (1) and the Wright-Malta steam injection pyrolysis process (2).

The program was conducted in two phases. The first phase was devoted to identifying processes that offer the potential for enhanced product recovery, an evaluation of chemical treatments to improve carbon recovery in pyrolysis processes, an evaluation of the Worcester Polytechnic and Wright-Malta processes, and a laboratory investigation of embrittlement processes for cellulose wastes. The second phase of the program was concerned with further laboratory studies of the embrittlement process, pilot studies of the embrittlement process with shredded newsprint and refuse-derived fuel (RDF), and an engineering analysis and economic assessment for a plant to process powdered cellulose for use as a fuel. A comprehensive description of the program conducted in Phase I was presented in a U.S. Environmental Protection Agency (EPA) report entitled, "Investigation of Advanced Thermal-Chemical Concepts for Obtaining Improved MSW-Derived Products." (3) This current report summarizes the results of Phase I and provides a comprehensive review of the work conducted in Phase II.

SECTION 2

CONCLUSIONS

PHASE I

The technology of cellulose chemistry provides several methods for processing the organic fraction of municipal solid waste (MSW) to obtain improved refuse-derived products. Laboratory processes for obtaining a carbon char and a cellulose powder have been identified. In addition, laboratory processes for obtaining liquid and gaseous fuels from solid wastes described in the literature were reviewed.

Several chemical treatments for promoting char formation at low temperatures were demonstrated. The patented process developed by Harendza-Harinxma (4) using $Na_2Al_2O_4$ to promote char production was evaluated for incorporation into the Black-Clawson (5) wet process. Markets for the char product were also investigated, but it was not possible to identify firm markets for the char. Lack of familiarity with the product and the need for rigid product specifications limited strong market acceptance.

During the course of Phase I, two processes for the production of liquid and gaseous fuels were also reviewed. Both the Worcester Polytechnic Institute process and the Wright-Malta Corporation process were selected because of their unique potential for enhanced product recovery. However, after review, it was concluded that neither process was practical for implementation on a large scale at present.

A major accomplishment of Phase I was the identification and laboratory verification of chemical treatments for cellulose embrittlement. As a result of preliminary laboratory studies, the basic requirements were defined for producing powdered material from the organic fraction of MSW. Although a number of the chemical treatments investigated were suitable for embrittling cellulose waste materials, HCl was found to be the most effective treatment agent. However, more quantitative measurements of the embrittlement process parameters were needed. The information obtained from these studies could provide the basis for a detailed engineering and economic analysis for a full-scale facility.

PHASE II

In Phase I several chemical treatments identified for cellulose embrittlement were investigated. Using a laboratory reactor samples of shredded newsprint were exposed to different concentrations of HCl, SO_2, and Cl_2 gases. HCl proved to be the most favorable reagent for large-scale cellulose waste processing. To evaluate better the process variables for cellulose embrittlement with HCl, a series of pilot reactor studies was conducted with shredded newsprint and RDF. From these studies, it was found that acceptable operating results were obtained at 149°C (300°F), a 6-min reaction time, and 50% by volume concentration of HCl in the reactive gas mixture. It was further determined that the degree of embrittlement could be improved by raising the treatment temperature to 177°C (350°F) and extending the reaction time to 8 to 10 min. From the data obtained in these experiments, it can be concluded that the degree of embrittlement is maximized with high treatment temperatures, long reaction times, minimum moisture content, and moderate levels of HCl concentration.

A number of mechanisms have been considered to account for the embrittlement observed in the treated cellulose. It is believed that the embrittlement process is not a single mechanism, but rather a complex combination of mechanisms. Both a reduction in the degree of polymerization and the formation of cross-links between polymer chains are believed to be among the dominant mechanisms for cellulose embrittlement in the presence of a mineral acid.

With data from the laboratory and pilot studies, a preliminary design for a resource recovery plant to produce powdered cellulose fuel (p-RDF) was developed. The design plan was based on the use of HCl gas for embrittlement. A preliminary economic analysis was also prepared. The plant would process 907 metric tons [mt] (1000 tons) per day and process 399 mt (440 tons) of p-RDF per day. The capital cost of the facility would be $30.3 million based on 1978 dollars. From the data developed, it was calculated that for the facility to break even, the fuel would have to sell for about $0.064/kg ($0.029/lb) if the plant charged a tipping fee of $9.37/mt ($8.50/ton).

SECTION 3

CARBONIZATION OF CELLULOSE

Thermal decomposition of refuse in the absence or partial absence of oxygen (pyrolysis) has been used for the production of useful fuels. Solid, liquid, or gaseous fuels can be obtained by a variety of pyrolysis processes. The quantity of char, bitumen-like liquid, and gas varies and is a function of the time-temperature sequence for each particular process. Commercial, pilot, and laboratory processes that use a variety of furnace designs have been developed to produce a wide range of fuel products.

The thermal processing employed can be designed to maximize the end products desired from the cellulose wastes. Higher heating rates and higher temperatures produce large quantities of gas and less char. Conversely, lower heating rates and lower temperature processes result in increased char production.

The quantity of char, the composition of the gases and liquids evolved, and the necessary reaction temperatures can be significantly affected by the presence of chemical agents in the cellulose materials. A number of chemical treatments have been identified that increase the quantity of char produced and decrease the amount of combustible gases and tars formed. Many of these treatments were developed for flame-proofing cellulosic materials. The highly effective flame-proofing compositions are all soluble in water, and most are salts of either strong acids or bases. In addition, many oxidizing agents attack cellulose and have been found to be effective fire retardants. Oxidized cellulose pyrolyzes rapidly at lower temperatures, giving high charcoal residues.

Although a number of pyrolysis processes have been developed to produce carbon char, the literature search only produced one process using chemical treatment to promote char formation. In the patented process developed by A. Harendza-Harinxma (4), sodium aluminate ($Na_2Al_2O_4$) is used to promote carbon formation at temperatures below 349°C (660°F). In most of the conventional pyrolysis processes reported in the literature, pyrolysis is achieved with thermal treatments from 499°C to 899°C (930°F to 1650°F). In addition, the char yield is reportedly increased for the sodium aluminate process (4).

During this project, three char-promoting materials; NH_4Cl, $CaCl_2$ and $Na_2Al_2O_4$ were evaluated. Thermogravimetric analysis was used to study the pyrolysis of cellulose samples treated with each of the chemicals of interest. The results of these preliminary studies showed that $Na_2Al_2O_4$ and NH_4Cl are promising char promoting chemicals. A sample of the carbon char produced from the pyrolysis of shredded newsprint treated with a 2% solution of $Na_2Al_2O_4$ is shown in Figure 1.

In Dr. Harendza-Harinxma's process, municipal refuse and sewage sludge are pyrolyzed to a char and fuel gas. In this process, sewage sludge is used as the solvent for a 2 to 4% solution of sodium aluminate. This solution is mixed with municipal refuse (two parts sludge to one part refuse). The slurry mixture is then mechanically dewatered, resulting in a thickened sludge which is thermally dried to about 15% moisture content. The dried refuse-sludge mixture, impregnated with sodium aluminate, is then carbonized for about 1 hr at 249°C to 299°C (480°F to 570°F).

A preliminary engineering study of a plant to produce carbon char from MSW and sewage sludge was conducted. Based on the information accumulated, a design for a low-temperature pyrolysis facility was developed (see Figure 2). The basic design for this plant is based on the Black-Clawson wet processing system at Franklin, Ohio (5). The process flow essentially follows the Black-Clawson process to the dewatering stage at the hydrodenser. After partial dewatering at the hydrodenser, the slurried refuse would be mixed with sodium aluminate and sewage sludge in a flash mixer. This slurry mixture would then be mechanically dewatered in a cone press and dried in a rotary carbonization kiln.

A plant processing 907 mt (1000 ton) of refuse per day could generate up to 272 mt (300 ton) of char per day or about 72,109 mt (79,500 ton) per year. A preliminary economic analysis based on 1978 dollars was prepared for this proposed pyrolysis plant. The proposed plant would have a total capital cost of $25,833,000. Revenues for the facility would be provided from several sources: a) a tipping fee ($8.50), b) sludge disposal ($5.00), c) sale of aluminum and iron ($3.65), and d) sale of carbon char. The estimated total operating cost would be $29.42/mt ($26.68/throughput ton) of MSW with a potential revenue of $18.91/mt ($17.15/throughput ton) plus the revenue from the sale of carbon char. For the pyrolysis facility to break even the carbon char would have to sell for $0.035/kg ($0.016/lb) or $35.3/mt ($32/ton) in order to cover the $9.53 deficit calculated between total operating cost and identified potential revenues. Of major concern is the market potential for the char product. If large quantities are to be produced, then suitable long term markets must be available.

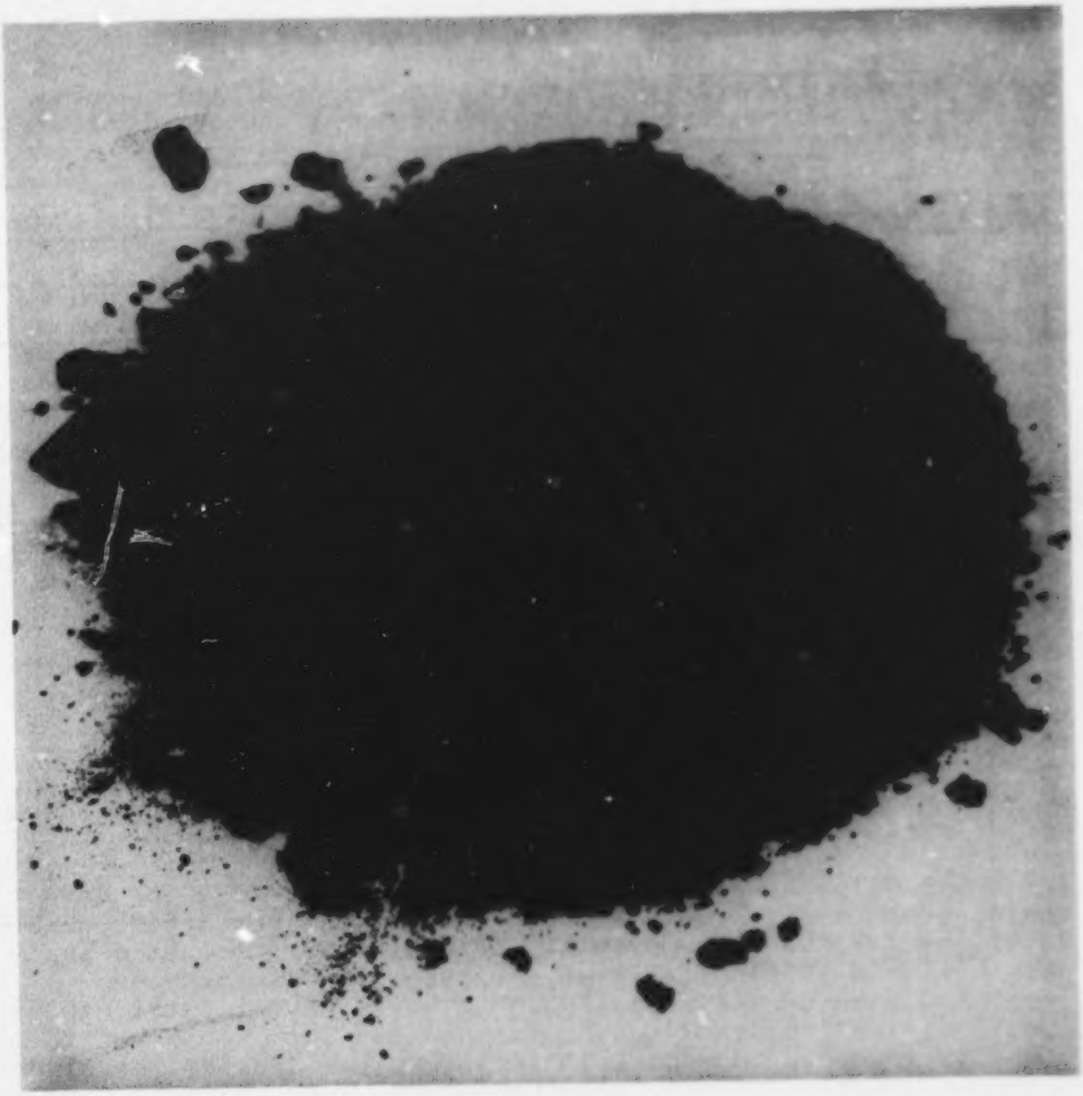

Figure 1. Carbon char prepared by pyrolysis of MSW treated with $Na_2Al_2O_4$.

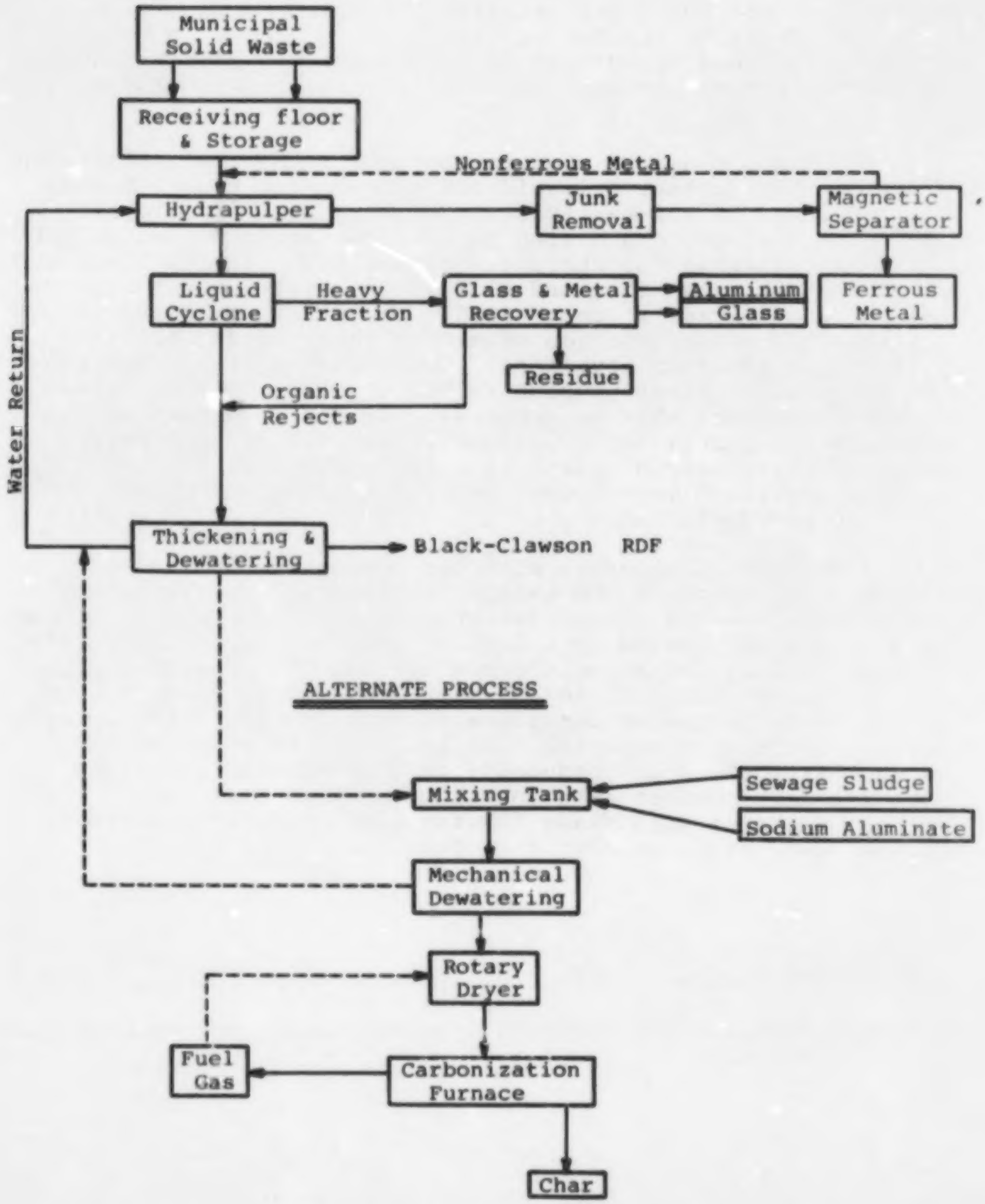
Municipal Solid Waste
Receiving floor & Storage
Nonferrous Metal
Hydrapulper
Junk Removal
Magnetic Separator
Liquid Cyclone
Heavy Fraction
Glass & Metal Recovery
Aluminum
Glass
Ferrous Metal
Residue
Organic Rejects
Water Return
Thickening & Dewatering
Black-Clawson RDF
ALTERNATE PROCESS
Mixing Tank
Sewage Sludge
Sodium Aluminate
Mechanical Dewatering
Rotary Dryer
Fuel Gas
Carbonization Furnace
Char

Figure 2. Flow plan for carbon char production.

A number of potential markets were identified for the char product from the pyrolysis process: a) solid fuel, b) feed stock for preparing gaseous or liquid fuels, and c) substitute for the carbon now being used in carbon and graphite products (activated carbon, charcoal, carbon fillers, carbon risers, etc.).

It appears that the char can be used as a solid fuel and as feed stock for synthetic liquid and gaseous fuels at a market value of about $0.022/kg ($0.01/lb). With some additional processing the char could also be utilized as an activated carbon, a raw material for charcoal briquettes, a carbon riser in iron and steel production and as fill in nonstructural rubber products at a market value of $0.044 to $0.088/kg ($0.02 to $0.04/lb). A major question regarding these latter applications is the availability of sufficient market demand for the char product. A plant processing 907 mt (1000 ton) of refuse per day could more than saturate many of the potential market opportunities identified (72,109 mt/year) (79,500 ton/year). Before a char-producing plant is built, therefore, it must secure a certified market for its product from one of the applications identified.

Preliminary discussion with the companies considered potential customers of the carbon char product revealed considerable reservations concerning the use of this product. These reservations were based on a lack of familiarity with the carbon char product and concern about the use of an untried material. The inability to guarantee consistent product composition also presented considerable problems for these potential customers. In addition, the inability to successfully commercialize the char produced from conventional pyrolysis processes developed to date (Baltimore, Occidental, etc.) further moderates enthusiasm for the char product produced by the low temperature pyrolysis process.

SECTION 4

POWDERED CELLULOSE

INTRODUCTION

The processes for converting the organic fraction (predominately cellulose) of MSW into a finely powdered material offered a number of advantages for improving the quality and marketability of the recovered products. In a powdered form, the MSW can be a more desirable fuel; it can be used in suspension fired boilers; it can be slurried with oil for firing in liquid fuel units; and it can be readily pelletized (6). In addition, the powdered MSW can be more readily used as a filler material in the fabrication of plastic and rubber products.

A number of thermal and chemical treatments have been described in the literature for promoting the conversion of the organic fraction in refuse to a fine powder (7). Since the major constituent of the organic fraction is cellulose (75%), the treatments are based primarily on the technology of cellulose processing. Most of these processes are chosen to embrittle or degrade the cellulose by reducing the degree of polymerization. In addition to degradation, certain acid treatments appear to promote crosslinking of adjacent molecules, which makes the cellulose rigid and brittle. Heating cellulose in air up to temperatures of 204°C (400°F) also will result in partial embrittlement. In addition, cellulose treated with formaldehyde also undergoes embrittlement.

PHASE I

During Phase I a number of chemicals were screened for their ability to embrittle paper and other cellulose wastes. The chemicals studied are as follows:

1. Formalin
2. Formalin plus CO_2
3. Formalin plus NO_2
4. Formalin plus formic acid
5. Formalin plus acetic acid
6. Formalin plus SO_2
7. Formalin plus HCl
8. Paraformaldehyde plus SO_2

9. Methylan plus SO_2
10. Acetal plus SO_2
11. Hydrochloric acid
12. Chlorine
13. Thionyl chloride.

The results of these initial studies showed that hydrochloric acid (HCl) is an extremely good embrittlement agent. Chlorine gas (Cl) and thionyl chloride ($SOCl_2$) also were found to be effective embrittlement agents. Sulfur dioxide (SO_2) proved to be a moderate embrittlement agent. The effectiveness of SO_2 was improved by the inclusion of formaldehyde in the reaction mixture.

The experimental arrangements used for the chemical treatment of the shredded samples is shown in Figure 3. After chemical treatment, the samples were pulverized and the powder obtained was evaluated. Examples of the powder obtained from several of these studies are shown in Figures 4 through 8.

PHASE II

A second series of experiments was conducted to define better the embrittlement reaction of shredded newsprint. Using the laboratory reactor and the experimental arrangement shown in Figure 3, 10 g (0.35 oz) samples of shredded newsprint were exposed to different concentrations of HCl, SO_2 and Cl_2 gases for 10 min. For the SO_2 treatment, the shredded newsprint was first sprayed with formaldehyde before exposure to the sulfur dioxide. The reactor temperature was kept at 90°C (194°F) by the use of a heating lamp. The quantity of reactant gases was regulated by partially evacuating the reactor, then backfilling it with the gas to atmospheric pressure. In this fashion various partial pressures of gases were evaluated and the mass of the gases at these pressures was calculated using the ideal gas equation.

Unreacted gases were passed through a fritted glass dispersion tube into a scrubber unit consisting of a three-neck, round bottom flask. The effectiveness of the scrubber system was determined by processing reactant gases through an empty reactor. In this procedure the reactor with a volume of 4.2 ℓ (1.1 gal) was first evacuated and then backfilled with reactant gases at atmospheric pressure and temperature. The total number of moles in the reactor was calculated using the ideal gas equation. The scrubber was filled with 1 ℓ (1.06 qt) of water to scrub HCl gas, and SO_2 was recovered by reacting it with 1 ℓ (1.06 qt) of 0.8% potassium chlorate solution in the scrubber. Recovery of chlorine gas required two scrubber units in series. The first unit was filled with a sodium sulfite solution (15% in excess of stoichiometric quantities). The second scrubber contained 0.8% potassium chlorate solution to

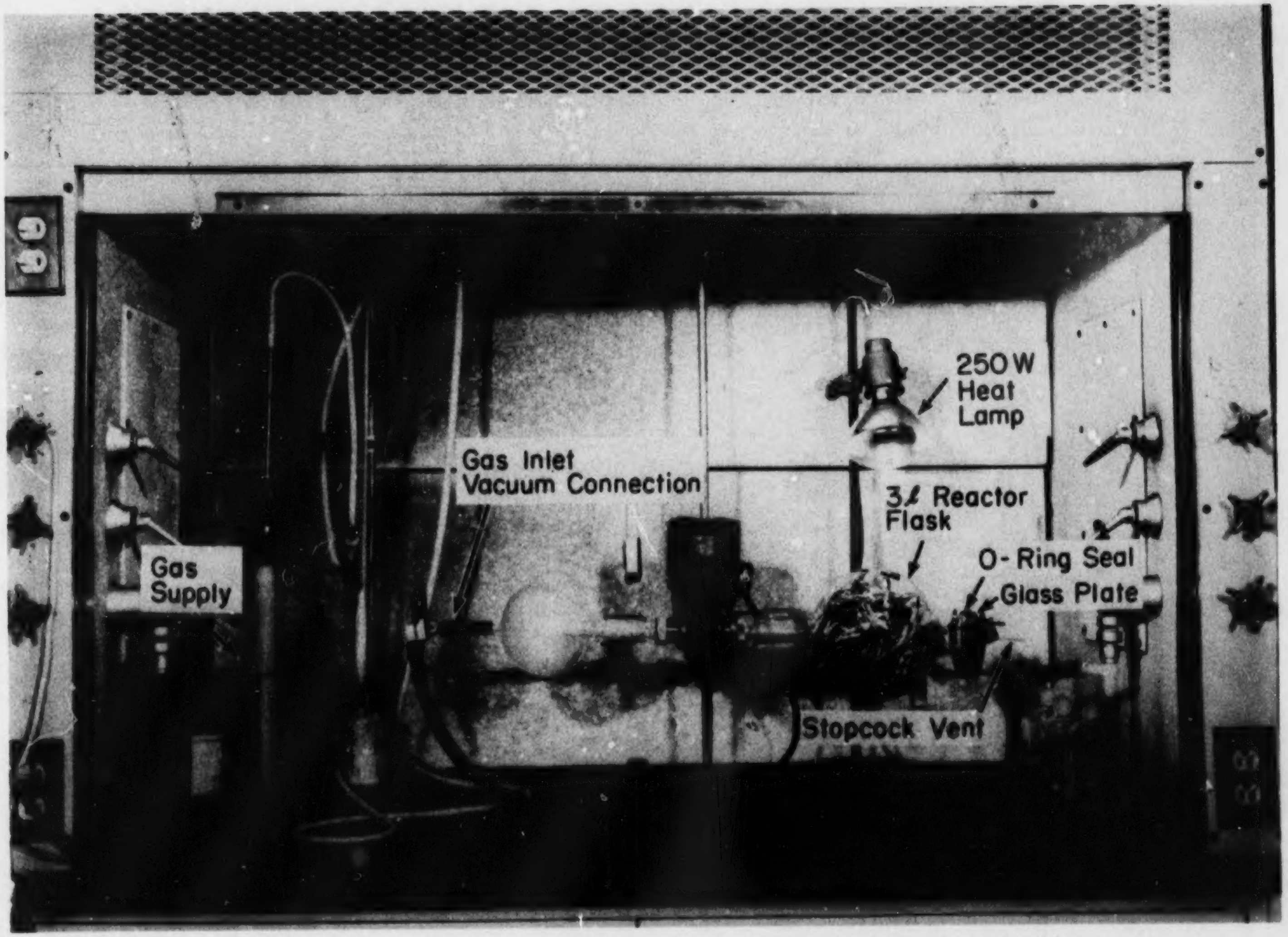
250 W
Heat
Lamp
3ℓ Reactor
Flask
O-Ring Seal
Glass Plate
Gas Inlet
Vacuum Connection
Gas
Supply
Stopcock Vent

Figure 3. Experimental arrangement used for embrittlement studies.

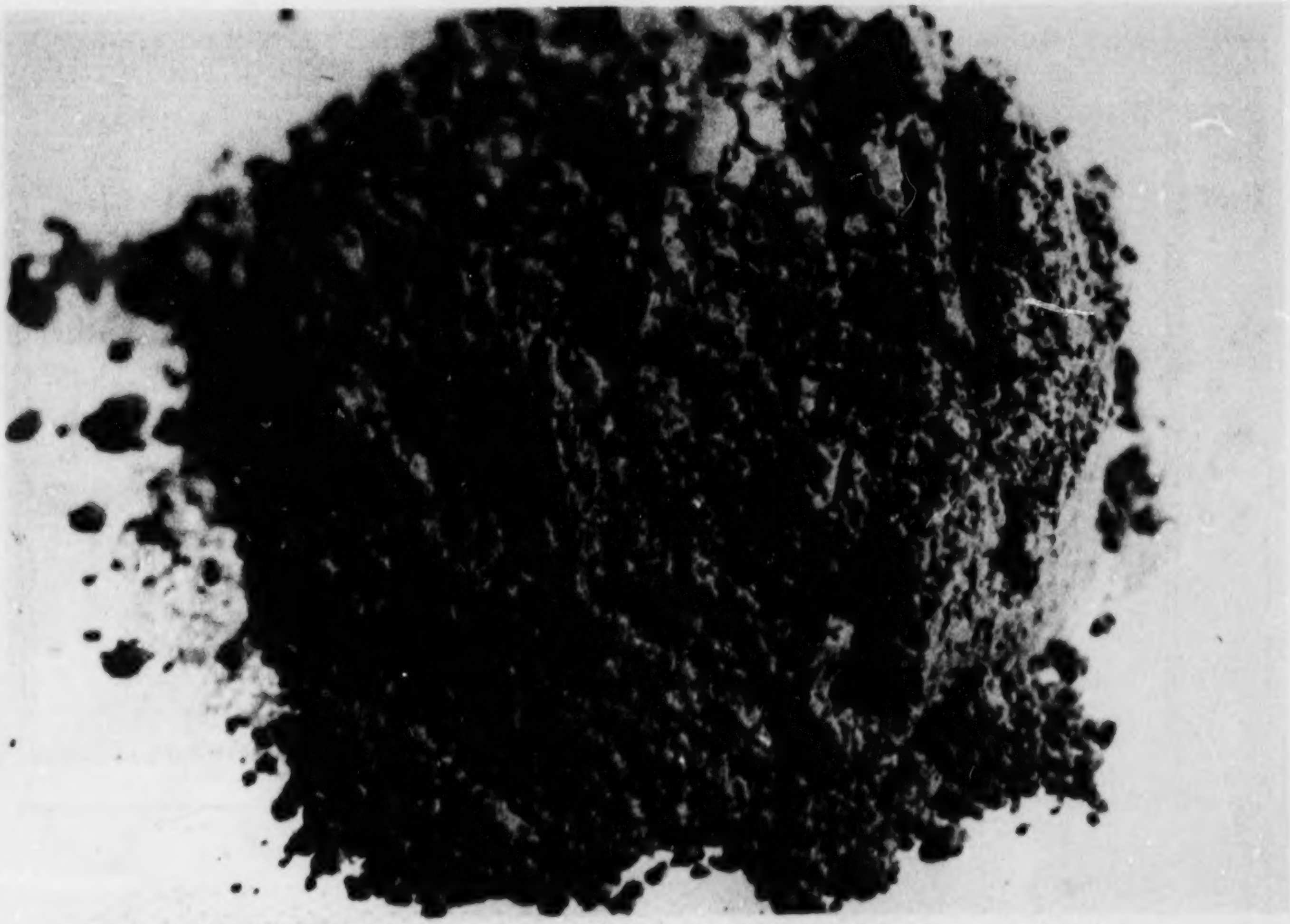

Figure 4. Shredded newspaper treated with $SOCl_2$ (thionyl chloride).

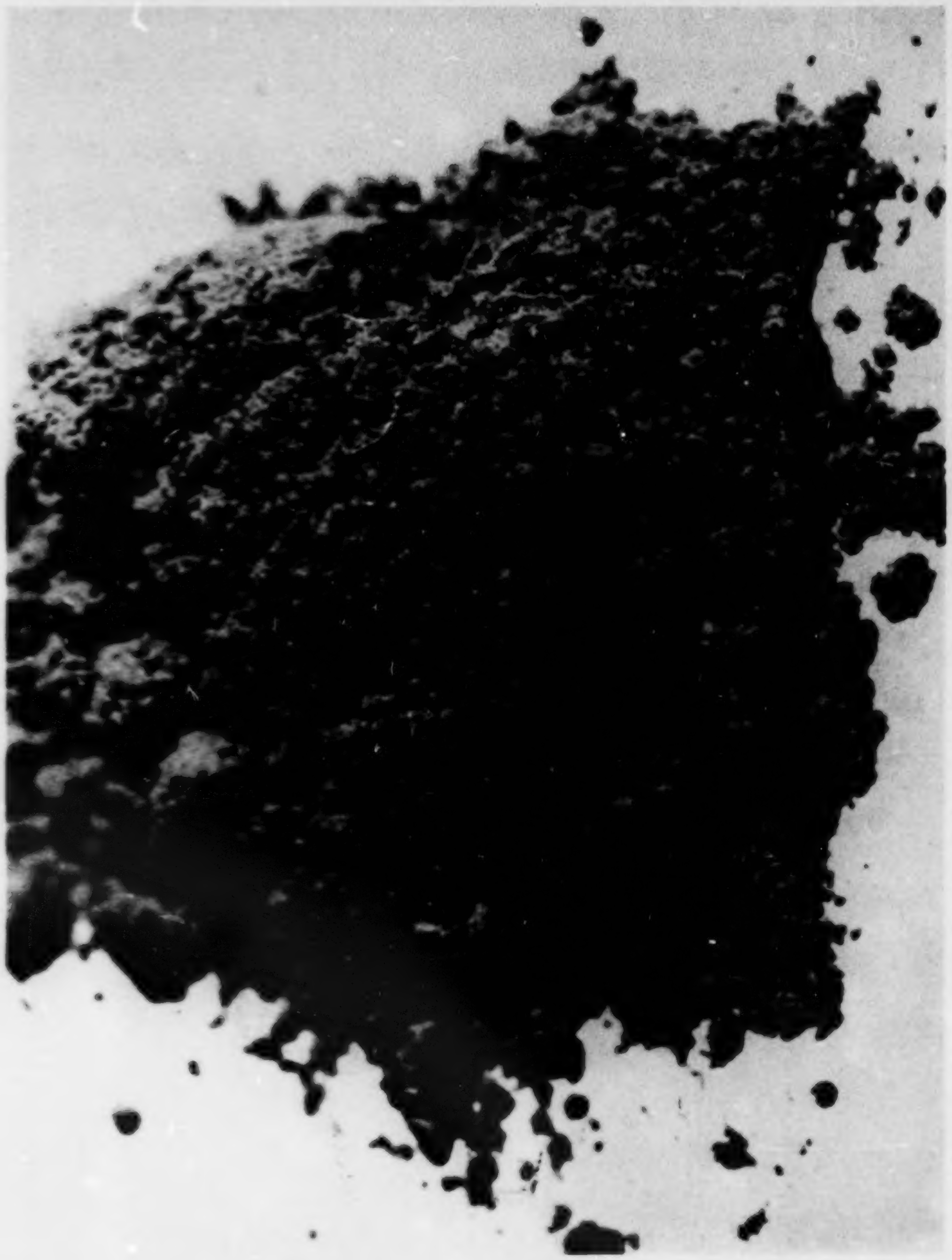

Figure 5. Shredded newspaper treated with para-formaldehyde and SO_2.

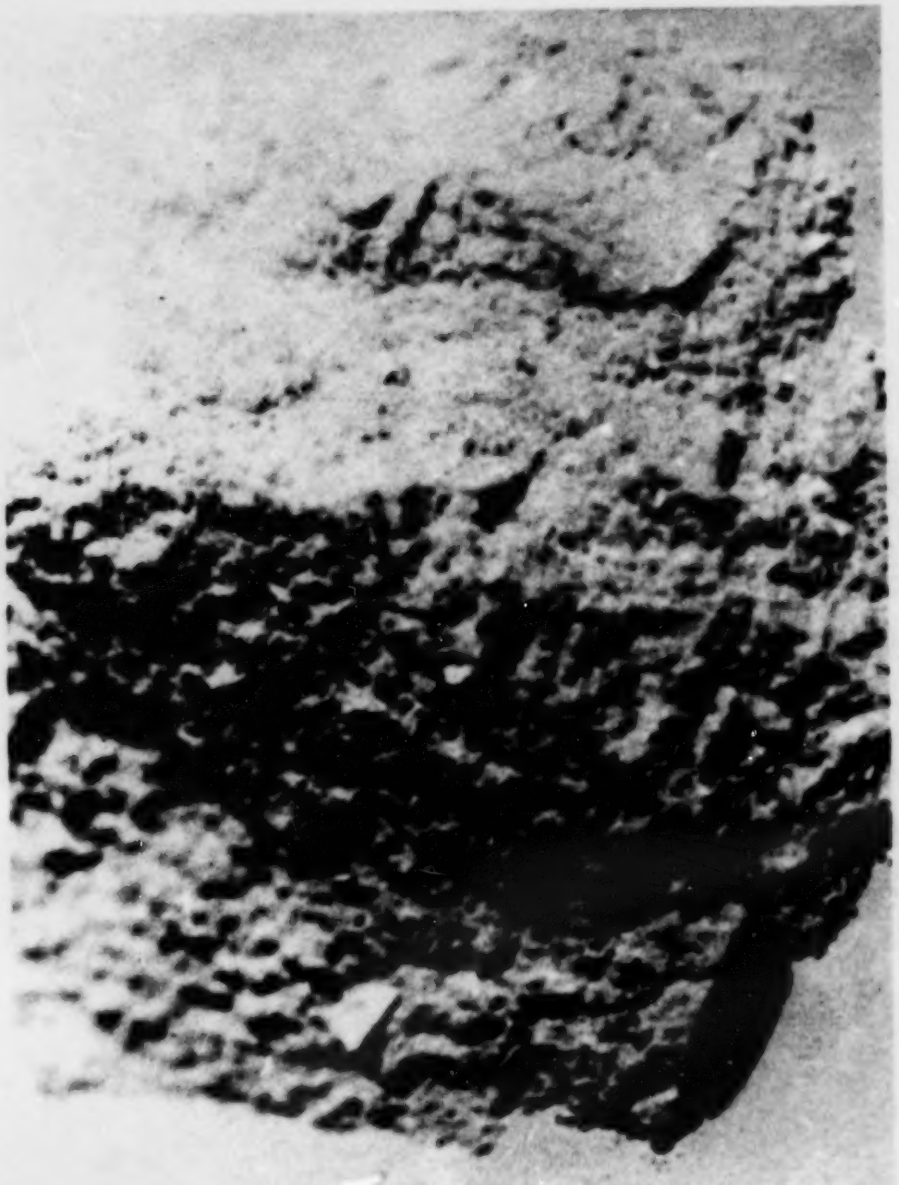

Figure 6. Computer paper treated with chlorine.

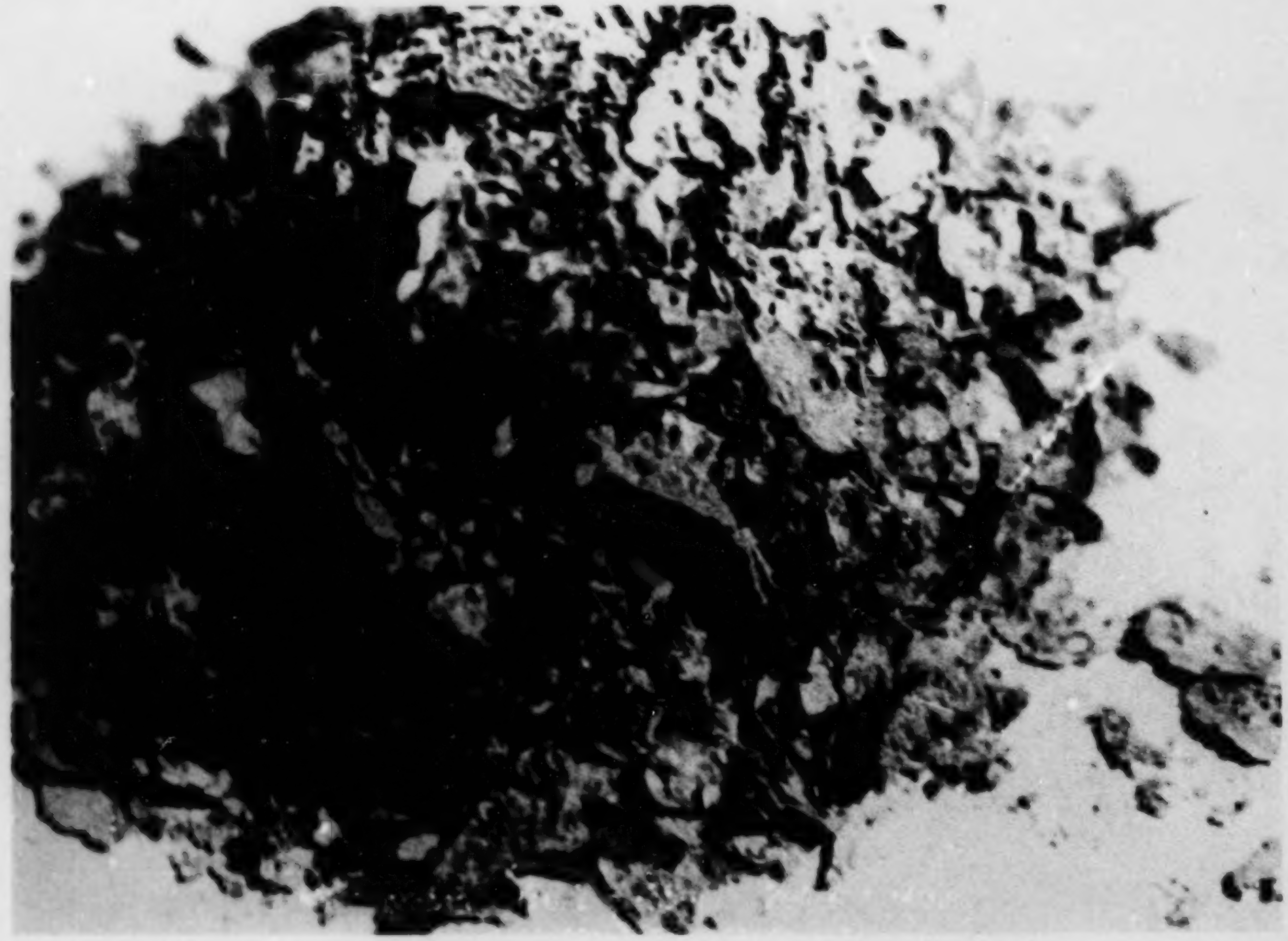

Figure 7. Shredded newspaper treated with formaldehyde in SO_2.

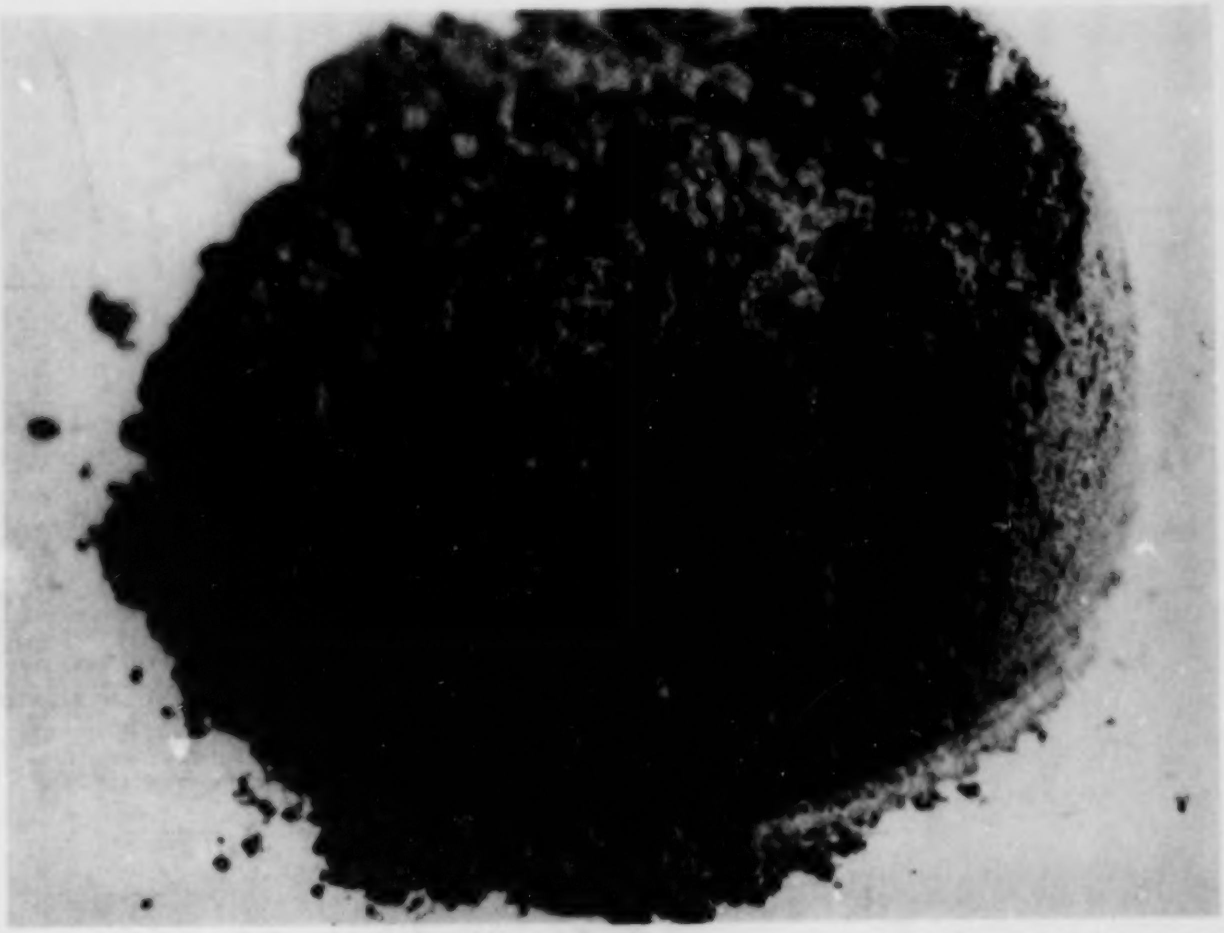

Figure 8. Shredded newspaper treated with hydrochloric acid.

react with the SO_2 formed in the first reactor. The following stoichiometric equations summarize the reactions for the recovery of Cl_2 and SO_2.

$$\left.\begin{array}{l} Na_2SO_3 + H_2O + Cl_2 \longrightarrow Na_2SO_4 + 2HCl \\ Na_2SO_3 + 2HCl \longrightarrow 2NaCl + H_2O + SO_2\uparrow \end{array}\right\} Cl_2 \text{ recovery}$$

$$KClO_3 + 3SO_2 + 3H_2O \longrightarrow KCl + 3H_2SO_4 \qquad SO_2 \text{ recovery}$$

The reaction between the gas and scrubber solution was carried out by gently drawing the gaseous content of the reactor into the scrubber for about one-half hour. In order to maximize the recovery, the gas was dispersed as fine bubbles in the scrubber solution by using a glass frit and stirring the solution with a magnetic stirrer. A 10 ml (0.34 oz) aliquot sample was taken after the completion of the reaction and titrated with 0.1N NaOH to determine the strength of the acid formed as a result of the stated reactions. Recovery of 95 to 98% of the reactant gases was achieved.

Evaluation of the embrittlement process by the various gas treatments was accomplished by placing an 8 cm (3.1 in) length of treated paper and a plastic breaker ball in a plastic vial. The vial was placed in a Wig-L-Bug (Crescent Dental Manufacturing Company) and the time required to powder the paper was recorded. Tables 1, 2, and 3 summarize the results of this second series of laboratory experiments.

The data presented in Tables 1, 2, and 3 show that approximately 2.9 g (0.1 oz) (79 mmole) HCl, 5.6 g (0.2 oz) (70 mmole) Cl_2, 6.5 g (0.23 oz) (102 mmole) SO_2 are consumed in the treatment of 10 g (0.35 oz) of shredded newspaper for embrittlement in a batch process. The data from Tables 1 and 2 show that the degree of embrittlement with HCl and Cl_2 is not affected if the initial quantities of the reactant gases consumed are in excess of or equal to the minimum required amount. When the quantity of reactant gas consumed is less than this value, poor embrittlement occurs.

The SO_2 consumed in the sulfur dioxide/formaldehyde embrittlement (Table 3) is almost twice the amount of HCl on a weight basis. In addition, the degree of embrittlement is lower as judged by the time required to powder these samples. The data also show that the degree of embrittlement can be improved by the further addition of formaldehyde. For example, with an SO_2 pressure of 710 mm Hg (15.7 lb/in^2), doubling the concentration of formaldehyde resulted in a sample which was powdered in one-third the time. At the same time, the amount of SO_2 consumed per 10 g (0.35 oz) of paper increased by 10 g (0.035 oz).

TABLE 1. LABORATORY RESULTS FOR HCl

Partial pressure of HCl [mm Hg (lb/in^2)]	Initial mass of HCl in the reactor [g (oz)]	Mass of HCl recovered in the scrubber after reaction [g (oz)]	Amount of HCl consumed per 10 g of paper [g (oz)]	Powder time (sec)
710 (13.7)	5.9 (0.21)	5.1 (0.18)	0.8 (0.03)	27
550 (10.6)	4.5 (0.16)	3.8 (0.13)	0.7 (0.02)	32
450 (8.7)	3.7 (0.13)	3.1 (0.11)	0.6 (0.02)	32
350 (6.8)	2.9 (0.10)	2.3 (0.08)	0.6 (0.02)	32
100 (1.9)	0.8 (0.03)	0.5 (0.02)	0.3 (0.01)	210

TABLE 2. LABORATORY RESULTS FOR Cl_2

Partial pressure of Cl_2 [mm Hg (lb/in^2)]	Initial mass of Cl_2 in the reactor [g (oz)]	Mass of Cl_2 recovered in the scrubber after reaction [g (oz)]	Amount of Cl_2 consumed per 10 g of paper [g (oz)]	Powder time (sec)
710 (13.7)	11.3 (0.4)	8.2 (0.29)	3.1 (0.11)	25
550 (10.6)	8.8 (0.31)	5.4 (0.19)	3.4 (0.12)	30
450 (8.7)	7.2 (0.25)	4.2 (0.15)	3.0 (0.11)	25
350 (6.8)	5.6 (0.2)	4.0 (0.14)	1.6 (0.06)	35
100 (1.9)	1.6 (0.06)	1.0 (0.04)	0.6 (0.02)	75

TABLE 3. LABORATORY RESULTS FOR SO_2

Partial pressure of SO_2 [mm Hg (lb/in^2)]	Initial wt of SO_2 in the reactor [g (oz)]	Initial mass of formaldehyde in the reactor [g (oz)]	Weight percent formaldehyde	Mass of SO_2 recovered in the scrubber [g (oz)]	Amount of SO_2 consumed per 10 g of paper [g (oz)]	Powder time (min)
710 (13.7)	10.3 (0.36)	1.2 (0.04)	10.4	8.7 (0.31)	1.6 (0.06)	3
710 (13.7)	10.3 (0.36)	3.0 (0.11)	22.5	7.7 (0.27)	2.6 (0.09)	1
550 (10.6)	8.0 (0.28)	1.6 (0.06)	16.7	6.4 (0.23)	1.6 (0.06)	2
450 (8.7)	6.5 (0.23)	1.3 (0.05)	16.7	5.2 (0.18)	1.3 (0.05)	2.6
100 (1.9)	1.5 (0.05)	1.7 (0.06)	(53.1)	1.2 (0.04)	0.3 (0.01)	(3.5)

In summary, these experiments showed that greater quantities of Cl_2 were required to achieve equivalent degrees of embrittlement to that achieved with HCl. The SO_2 required for the sulfur-dioxide formaldehyde embrittlement was almost twice as much as that required with HCl. In addition, the degree of embrittlement by this process was not as complete as that observed for the HCl and Cl_2 treatments. The time that was required to powder the SO_2 treated samples was much greater than that required for the HCl or Cl_2 treated materials. These laboratory studies showed HCl to be the most suitable reagent compared to the Cl_2 and SO_2 treated samples.

Treated samples were analyzed with Electron Spectroscopy for Chemical Analysis (ESCA) and standard chemical analysis to investigate the embrittlement reaction. The ESCA results (Table 4) show very little (<1% atomic) chlorine is present in untreated paper or in samples treated with HCl. Similarly, samples treated with SO_2 and formaldehyde did not show any significant increase in sulfur content. However, significant chlorine incorporation did result from Cl_2 treatment. These results are in good qualitative agreement with the chemical analysis shown in Table 5.

PILOT REACTOR STUDIES

A third series of experiments studying the embrittlement of shredded waste with HCl was also conducted in order to evaluate process variables in a pilot size reactor. Shredded newsprint was used as the feed material for a major portion of the testing period. However, a number of embrittlement tests were also conducted using refuse derived fuel (RDF) from the Americology Plant in Milwaukee. Operational problems with the reactor system were analyzed through the study and reactor performance was closely monitored.

The reactor unit (shown in Figures 9 and 10), built by the University of Dayton Research Institute (UDRI), was designed to process 1.1 to 2.3 kg (2-1/2 to 5 lb) of shredded waste (newsprint or RDF) samples with a continuous flow of reactant gases. The interior of the reactor was constructed from a 30 gal carbon steel drum coated with a 20 mil thickness of Emralon* 314 (50% Teflon - 50% epoxy). The reactor is supported in a Unistrut frame such that it could be loaded and unloaded by tilting it about a horizontal axis between two vertical Unistrut channels. The shredded waste was introduced at the top and the lid was sealed with a specially designed silicone rubber gasket and locking ring to prevent leakage. Three 1800 watt drum heaters were installed on the outside of the reactor for heating. A stainless steel screen with 0.84 cm (0.33 in) diameter holes was installed at the bottom of the reactor to ensure an even

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* Acheson Colloid Company, Michigan

TABLE 4. QUALITATIVE AND SEMIQUALITATIVE ESCA ANALYSIS OF THE TREATED AND UNTREATED CELLULOSE (INTENSITY IN TERMS OF THE NORMALIZED ATOMIC PERCENT)*

Element	Level	Binding Energy (%)	Untreated newspaper (%)	Untreated filter paper (%)	Filter paper treated with HCl (%)	Newspaper treated with Cl_2 (%)	Newspaper treated with SO_2 and CH_2O (%)
Oxygen	1s	285	24.83	53.70	50.07	9.19	13.50
Carbon	1s	533	74.68	45.66	49.50	63.74	85.81
Chlorine	2p	197	0.49	0.64	0.42	27.08	0.32
Sulfur	2p	165	--	--	--	--	0.37

* These analyses ignore atomic hydrogen concentrations since the ESCA technique is unable to analyze hydrogen.

TABLE 5. CHEMICAL ANALYSES

Sample	% S	% Cl
1. Newsprint treated with HCl	--	1.05
2. Newsprint treated with Cl_2	--	5.49
3. Newsprint treated with SO_2-CH_2O	0.43	--
4. Untreated newsprint	0.22	0.09

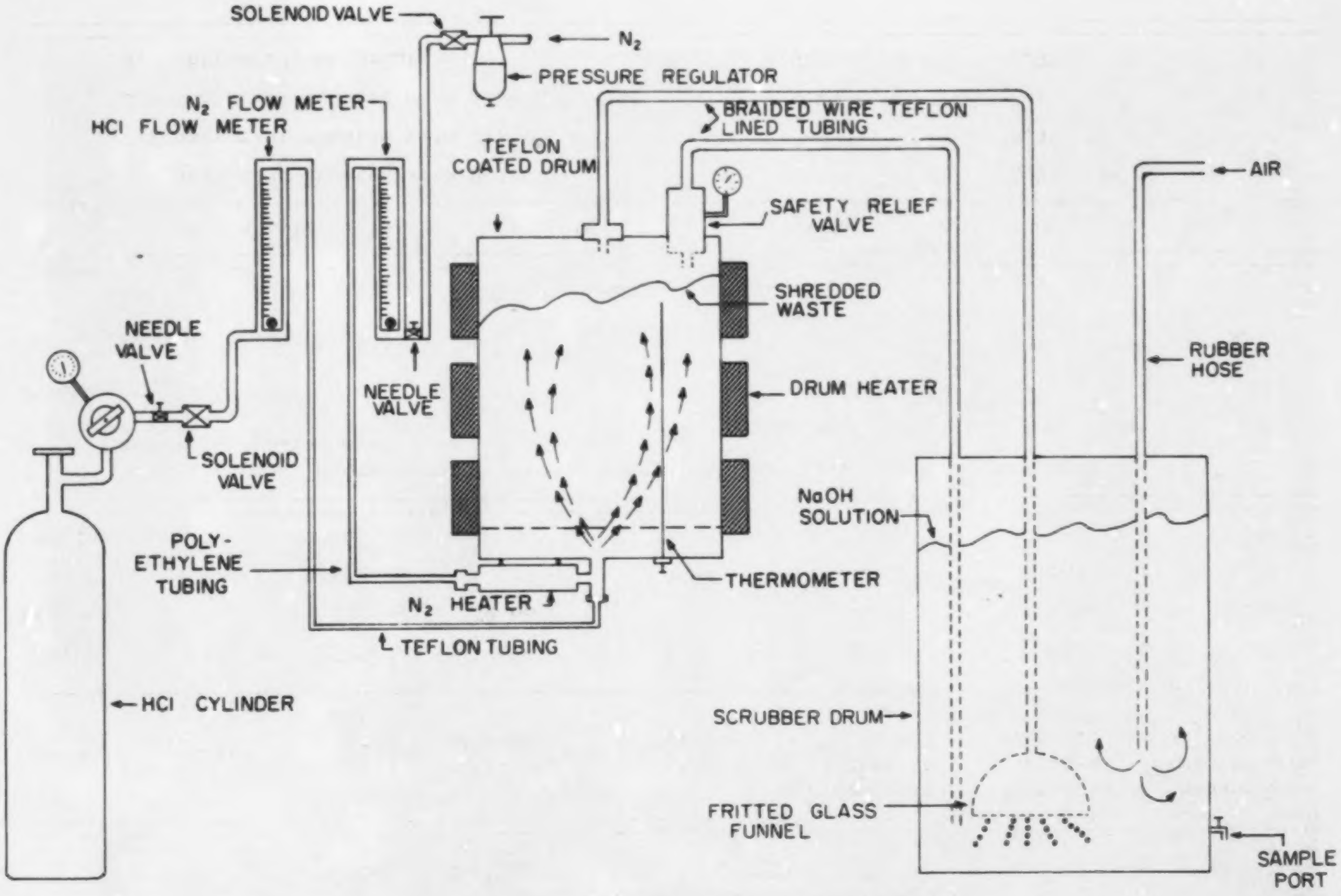

SOLENOID VALVE
N_2
PRESSURE REGULATOR
N_2 FLOW METER
HCl FLOW METER
BRAIDED WIRE, TEFLON LINED TUBING
TEFLON COATED DRUM
AIR
SAFETY RELIEF VALVE
SHREDDED WASTE
NEEDLE VALVE
NEEDLE VALVE
RUBBER HOSE
DRUM HEATER
SOLENOID VALVE
NaOH SOLUTION
POLY-ETHYLENE TUBING
THERMOMETER
N_2 HEATER
TEFLON TUBING
HCl CYLINDER
SCRUBBER DRUM
FRITTED GLASS FUNNEL
SAMPLE PORT

Figure 9. Process flow diagram for pilot reactor.

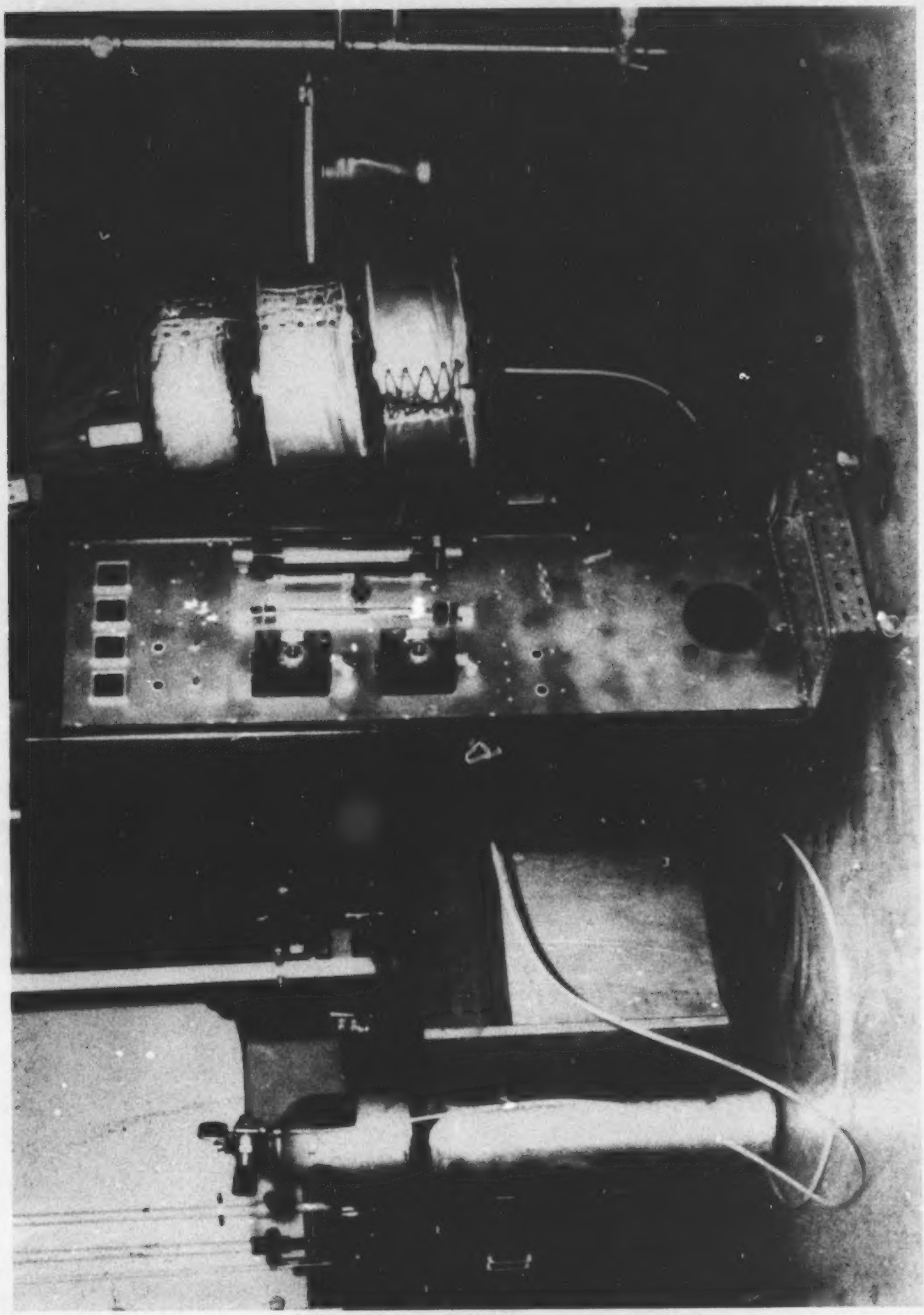


Figure 10. Pilot reactor.

distribution of the gas, and a Teflon relief valve was installed on the lid to provide safety from excessive pressures. All temperature measurements were made with a digital thermometer.

Hydrogen chloride was supplied from a 27.2 kg (60 lb) HCl cylinder, and N_2 was drawn from an existing N_2 bank. A 5 kW heater was used to heat the N_2. Two glass rotameters (0-35 ft^3/min) (0 99.1 ℓ/min) were used to measure the rate of the reactant gases flowing through the reactor.

The scrubber unit consisted of a polyvinyl chloride-lined 208.2 ℓ (55 gal) drum containing 84 ℓ (22.2 gal) of 0.15N sodium hydroxide solution. The unreacted gases were dispersed through a 15.2 cm (6 in) diameter fritted glass funnel into the NaOH solution. Efficiency of the scrubber was tested by introducing a known quantity of HCl, and titrating a 10 ml (0.34 oz) sample from a 500 ml (16.9 oz) aliquot of the scrubber solution with 0.1N HCl. A series of tests showed that the titrimetric data could account for approximately 95% of the quantity of HCl calculated from flow measurements.

After the reactor was charged with 1.1 kg (2-1/2 lb) of shredded waste, it was sealed and heated to the desired temperate with the drum heaters. Upon reaching the specified temperature, a moderate flow of HCl and N_2 was begun. The HCl flow was maintained for a short time to provide the desired quantity of this reactant. The reactor was then purged with N_2 for an additional 0.5 hr. Gas flow rates and times were recorded from the control panel. Unreacted HCl and the N_2 passed out the top of the reactor through a 1.9 cm (3/4 in) Teflon lined tube and into the scrubber unit described above. Two aliquots of the scrubber solution were titrated with 0.1N HCl to account for the amount of unreacted HCl. The input to the reactor was calculated from the flow rate of HCl at the measured pressure and temperature. Output of HCl from the reactor was calculated from the change in normality of the NaOH solution. The retention of HCl could be determined by the difference in these two values.

After chemical treatment, the shredded waste was ball milled for 15 min. The ball mill unit consisted of a 12.3 ℓ (13 qt) ceramic jar filled with 13.6 Kg (30 lb) of 1.3 cm (1/2 in) x 1.3 cm (1/2 in) ceramic cylindrical grinding pellets. The jar was rotated on a pair of 5.1 cm (2 in) diameter hard rubber rollers, one of which was chain driven by a 186.4 watt (1/4 hp) electric motor. Quartered samples of the powder were screened on a RoTap shaker for 10 min. The fractions retained on the 354, 149, and 74 μ (45 100 and 300 mesh) screens were weighed and recorded. The minus 354 μ (45 mesh) fraction was selected as the criterion for comparing the extent of embrittlement which resulted from each of the treated samples.

During this part of the study, the effects of several major processing variables on the embrittlement of shredded waste were studied. The roles of processing temperature, reaction time, HCl concentration, and moisture content of the sample were studied using the reactor system shown in Figure 9. The ranges evaluated for each of the process variables are shown in Table 6. Both shredded newsprint and RDF from the Americology Plant were used for this series of tests. Depending on the specific circumstances, each test condition was evaluated two to seven times for each of the process variables studied. Three runs were made for most of the test conditions. Heating times of about 15 min were required for the tests conducted at 149°C (300°F). The data recorded for each test series (temperature effects, reaction time, etc.) are compiled in Tables 7 through 12. The results from each test are also plotted in Figures 11 through 16.

As shown in Tables 7 and 8, and Figures 11 and 12, the degree of embrittlement increases with increasing treatment temperature; conversely, the amount of HCl consumed in the reaction decreases with increasing temperature. The decrease in the quantity of HCl retained in the shredded waste with increasing temperature may be due to physical desorption mechanisms which are more active with temperature (see Embrittlement Mechanisms section). Preliminary experiments also suggest that the use of treatment temperatures higher than those used would result in even greater levels of embrittlement. The treatment temperature selected for a full scale process should be a balance between the level of embrittlement required and the energy demands. In addition, the reduced amount of HCl consumed at higher reaction temperatures might encourage the use of somewhat higher temperatures to achieve greater embrittlement.

As shown in Tables 9 and 10, and Figures 13 and 14, the degree of embrittlement increases with increased reaction time. The longer exposure of the material to heat and HCl treatment also resulted in a greater amount of HCl consumed in the reaction. As with temperature, the reaction time used for a full scale process would be a balance between the level of embrittlement desired versus the energy demand and HCl requirements.

The degree of embrittlement and the consumption of HCl in the reaction increased with increasing quantities of HCl in the reactant gases (Table 11, Figure 15). The consumption of HCl in the reaction followed a uniform progression whereas increasing embrittlement followed a stepwise progression. The maximum increase in embrittlement was observed at the 40 volume percent level. Longer reaction times increased embrittlement more effectively than the higher HCl concentrations.

The degree of embrittlement decreased with increasing initial moisture levels in the shredded waste samples studied.

TABLE 6. RANGES OF PROCESS VARIABLES EVALUATED

Variable	Range
Newsprint samples:	
Temperature, °C (°F)	97.8 (208) 122.8 (253) 148.9 (300)
HCl concentration, vol %	15 25 48 75
Reaction time, min	1 2 3 4 5 6
RDF samples:	
Temperature, °C (°F)	154.4 (310) 176.7 (350) 203.9 (399)
Moisture content, %	10 15 25 40
Reaction time, min	1 2 3 6 8

TABLE 7. EFFECT OF TEMPERATURE ON SHREDDED NEWSPAPER*

Reactor conditions							Product particle size distribution (cumulative retained)			
Avg. temp. [°C (°F)]	Time to temperature (min)	Flow rate of HCl [ℓ/min (cfm)]	Flow rate of N_2 [ℓ/min (cfm)]	Treatment time (min)	Concentration of HCl (vol %)	HCl consumed in process g/g†	45 Mesh (354 microns) (wt %)	100 Mesh (149 microns) (wt %)	200 Mesh (74 microns) (wt %)	Pan (wt %)
97.8 (208)	8.4	17.6 (.62)	20.4 (.72)	3	46.3	2.7	64.5	70.8	86.9	100
122.8 (253)	10.0	17.6 (.62)	20.4 (.72)	3	46.3	2.1	62.3	69.1	86.6	100
150.6 (303)	15.4	17.3 (.62)	18.9 (.67)	3	48.0	1.8	60.	67.6	86.3	100

* Sample size - 1.1-kg (2-1/2-lb) shredded newsprint.
The 303°F results are the average of 7 runs.
The 253°F results are the average of 3 runs.
The 208°F results are the average of 4 runs.

† g HCl/g sample

TABLE 8. EFFECT OF TEMPERATURE (RDF)*

Reactor conditions							Product particle size distribution (cumulative retained)			
Avg. temp. [°C (°F)]	Time to temperature (min)	Flow rate of HCl [ℓ/min (cfm)]	Flow rate of N_2 [ℓ/min (cfm)]	Treatment time (min)	Concentration of HCl (vol %)	HCl consumed in process g/g†	45 Mesh (354 microns) (wt %)	100 Mesh (149 microns) (wt %)	200 Mesh (74 microns) (wt %)	Pan (wt %)
154.4 (310)	11.1	17.6 (.62)	20.4 (.72)	3	46.3	.029	46.3	55.9	75.7	100
176.7 (350)	12.1	17.6 (.62)	20.4 (.72)	3	46.3	.027	45.8	56.6	79.0	100
203.9 (399)	18.9	17.6 (.62)	20.4 (.72)	3	46.3	.024	41.3	51.1	71.9	100

* The 399°F results are the average of 3 runs.
The 310°F results are the average of 3 runs.
The RDF° sample weighed 1.1-kg (2-1/2 lb).

TABLE 9. EFFECT OF TREATMENT TIME FOR SHREDDED NEWSPRINT*

Reactor conditions						Product particle size distribution (cumulative retained)			
Treatment time (min)	Flow rate of HCl [ℓ/min (cfm)]	Flow rate of N_2 [ℓ/min (cfm)]	Avg. temp. [°C (°F)]	Concentration of HCl (vol %)	HCl consumed in process g/g+	45 Mesh (354 microns) (wt %)	100 Mesh (149 microns) (wt %)	200 Mesh (74 microns) (wt %)	Pan (wt %)
1	17.0 (.60)	20.4 (.72)	152.8 (307)	45.0	.007	71.4	76.7	89.9	100
2	17.6 (.62)	20.4 (.72)	152.2 (306)	46.3	.012	62.5	64.7	85.7	100
3	17.3 (.61)	18.9 (.67)	150.6 (303)	46.0	.018	60.0	67.6	86.3	100
4	17.3 (.61)	20.4 (.72)	153.3 (308)	46.0	.024	55.2	64.8	87.4	100
5	17.8 (.63)	20.4 (.72)	153.3 (308)	46.6	.028	57.4	67.6	85.9	100
6	17.3 (.61)	20.4 (.72)	149.4 (301)	46.0	.033	52.2	63.5	84.1	100

* Sample size - 1.13-kg (2-1/2-lb) shredded newsprint.
The 1 minute results are the average of 2 runs.
The 3 minute results are the average of 7 runs.
All remaining results are the average of 3 runs.
+ g HCl/g sample

TABLE 10. EFFECT OF TREATMENT TIME FOR (RDF)*

Reactor conditions						Product particle size distribution (cumulative retained)			
Treatment time (min)	Flow rate of HCl [ℓ/min (cfm)]	Flow rate of N_2 [ℓ/min (cfm)]	Avg. temp. [°C (°F)]	Concentration of HCl (vol %)	HCl consumed in process g/g+	45 Mesh (354 microns) (wt %)	100 Mesh (149 microns) (wt %)	200 Mesh (74 microns) (wt %)	Pan (wt %)
1.0	17.6 (.62)	20.4 (.72)	151.7 (305)	46.3	.011	COULD NOT	BE BALL	MILLED	100
3.0	17.6 (.62)	20.4 (.72)	154.4 (310)	46.3	.029	46.3	55.9	75.7	100
6.0	17.6 (.62)	20.4 (.72)	158.9 (318)	46.3	.037	35.6	44.6	65.6	100
8.0	17.6 (.62)	20.4 (.72)	160.0 (320)	46.3	.039	35.2	44.8	64.7	100

* The 3-min results are the average of 3 runs.
The RDF sample weighed 1.13-kg (2-1/2 lb).

TABLE 11. EFFECT OF HCl CONCENTRATION ON SHREDDED NEWSPRINT

Reactor conditions						Product particle size distribution (cumulative retained)			
Concentration of HCl (Vol %)	Avg. temp. [°C (°F)]	Flow rate of HCl [ℓ/min (cfm)]	Flow rate of N_2 [ℓ/min (cfm)]	Treatment Time (min)	HCl consumed in process [g/g]+	45 Mesh (354 microns) (wt %)	100 Mesh (149 microns) (wt %)	200 Mesh (74 microns) (wt %)	Pan (wt %)
15	149.0 (301)	8.5 (.30)	48.0 (1.7)	3	.012	74.5	79.1	90.3	100
25	149.0 (301)	8.5 (.30)	25.5 (.9)	3	.015	73.15	78.2	89.9	100
48	150.5 (303)	17.3 (.61)	18.9 (.67)	3	.018	60.0	67.6	86.3	100
75	150.5 (303)	25.5 (.90)	8.5 (.30)	3	.026	58.8	67.2	88.4	100

NOTE: Sample size - 1.13-kg (2-1/2-lb) shredded newsprint.
The 15% results are the average of 2 runs
The 25% results are the average of 2 runs
The 48% results are the average of 7 runs
The 75% results are the average of 3 runs

+ g HCl/ g sample

TABLE 12. EFFECTS OF MOISTURE ON SHREDDED NEWSPRINT*

Reactor conditions							Product particle size distribution (cumulative retained)			
Moisture added to paper (%)	Flow rate of HCl [ℓ/min (cfm)]	Flow rate of N_2 [ℓ/min (cfm)]	Avg. temp. [°C (°F)]	Concentration of HCl (vol %)	Treatment Time (min)	HCl consumed in process [g/g]+	45 Mesh (354 microns) (wt %)	100 Mesh (149 microns) (wt %)	200 Mesh (74 microns) (wt %)	Pan (wt %)
10	18.1 (.64)	20.4 (.72)	154.4 (310)	47.0	3	0.025	61.1	68.7	86.1	100
15	16.6 (.62)	20.4 (.72)	151.1 (305)	46.3	3	0.028	64.3	71.6	89.2	100
25	17.6 (.62)	20.4 (.72)	156.1 (313)	46.3	3	0.047	65.5	78.9	96.4	100
40	17.6 (.62)	20.4 (.72)	157.2 (315)	46.3	3	0.056	+	+	+	+

* Sample size - 1.1-kg (2-1/2-lb) shredded newsprint.
The 10% moisture results are the average of 5 runs.
The 15% moisture results are the average of 3 runs.
The 25% moisture results are the average of 2 runs.

Only 1 run was made at 40% moisture because embrittlement was inefficient, and ball milling of this sample was not possible.

+ Could not be ball milled.

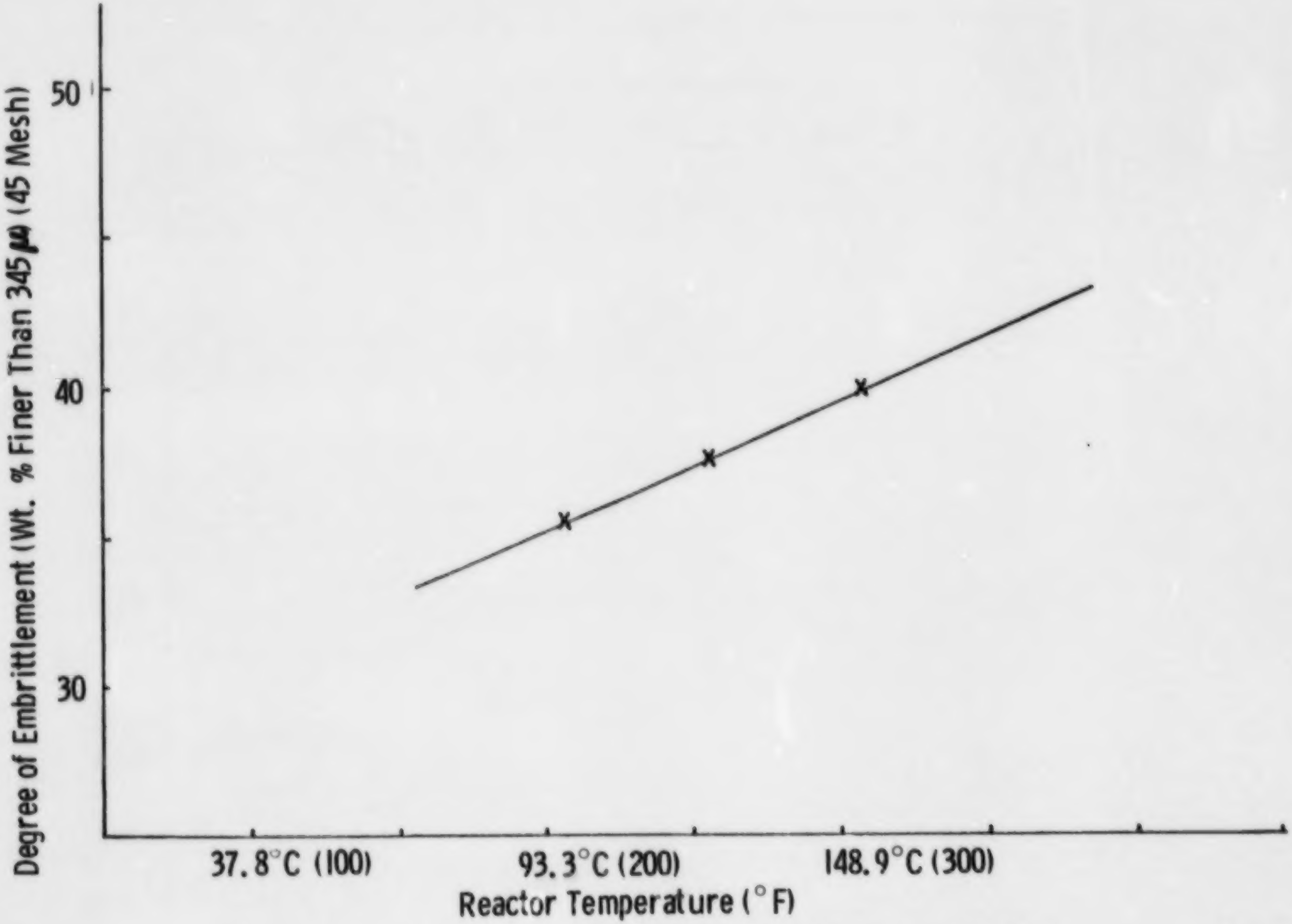


Figure 11. Effect of temperature (shredded newsprint).

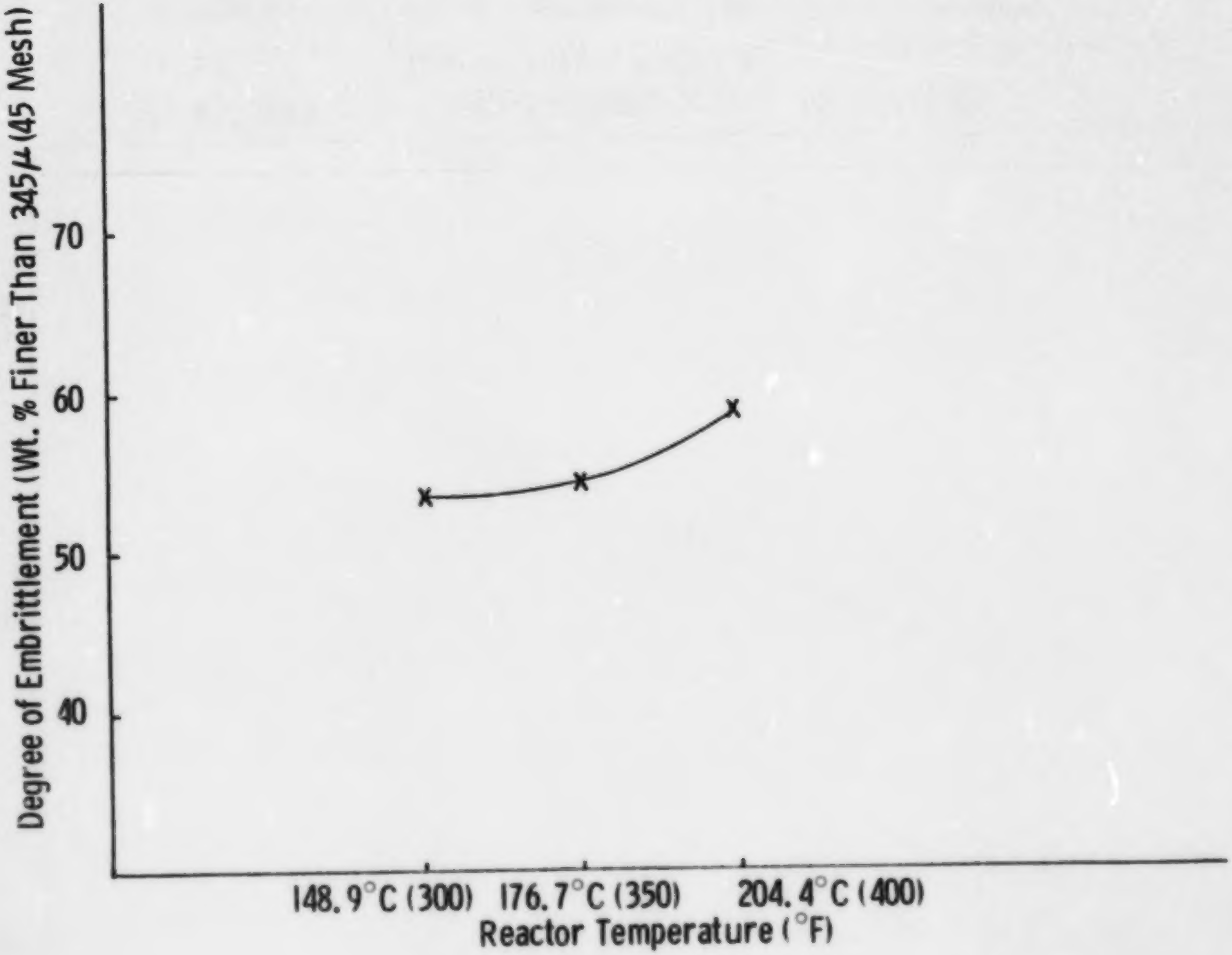


Figure 12. Effect of Temperature (RDF).

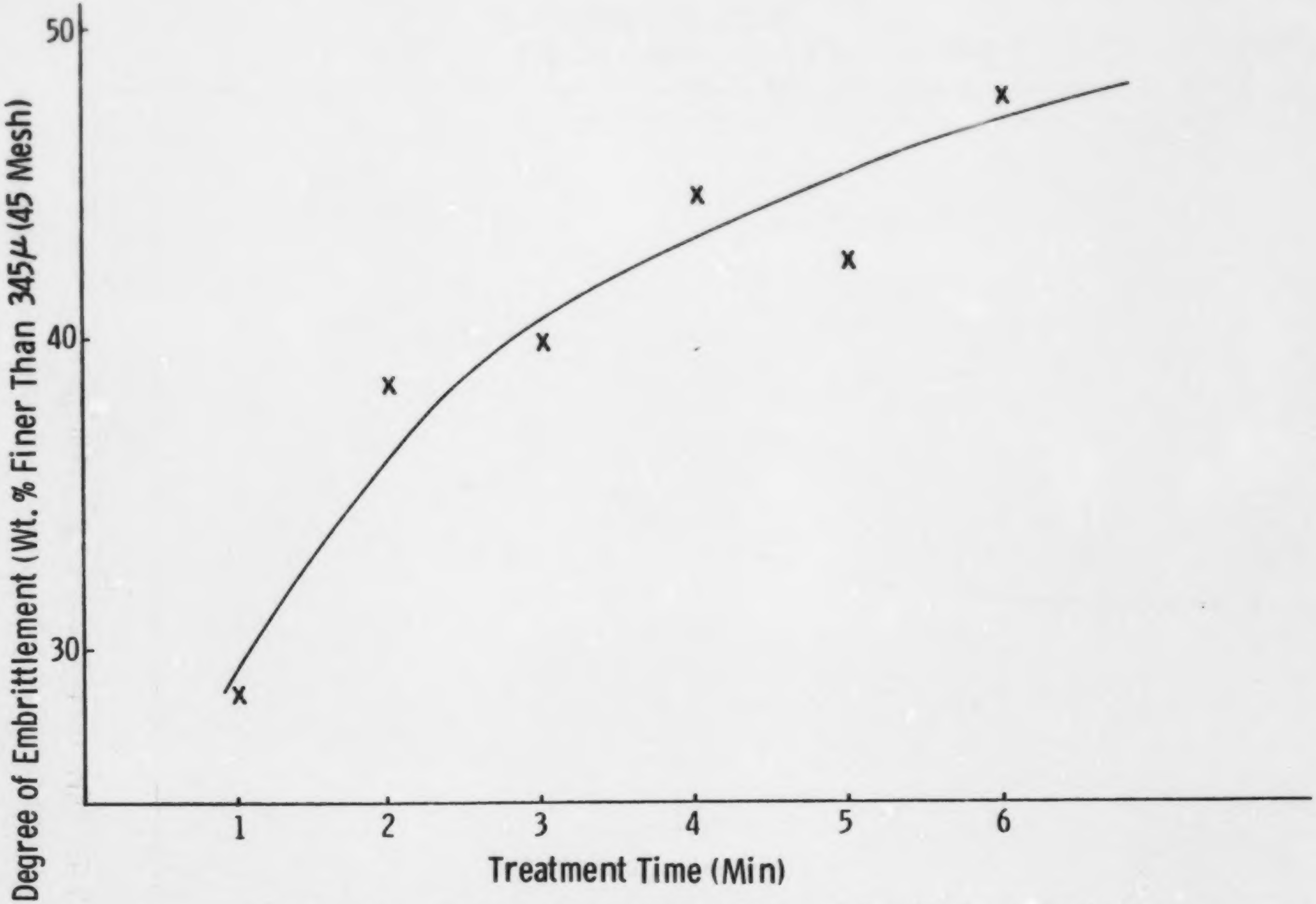


Figure 13. Effect of treatment time (shredded newsprint).

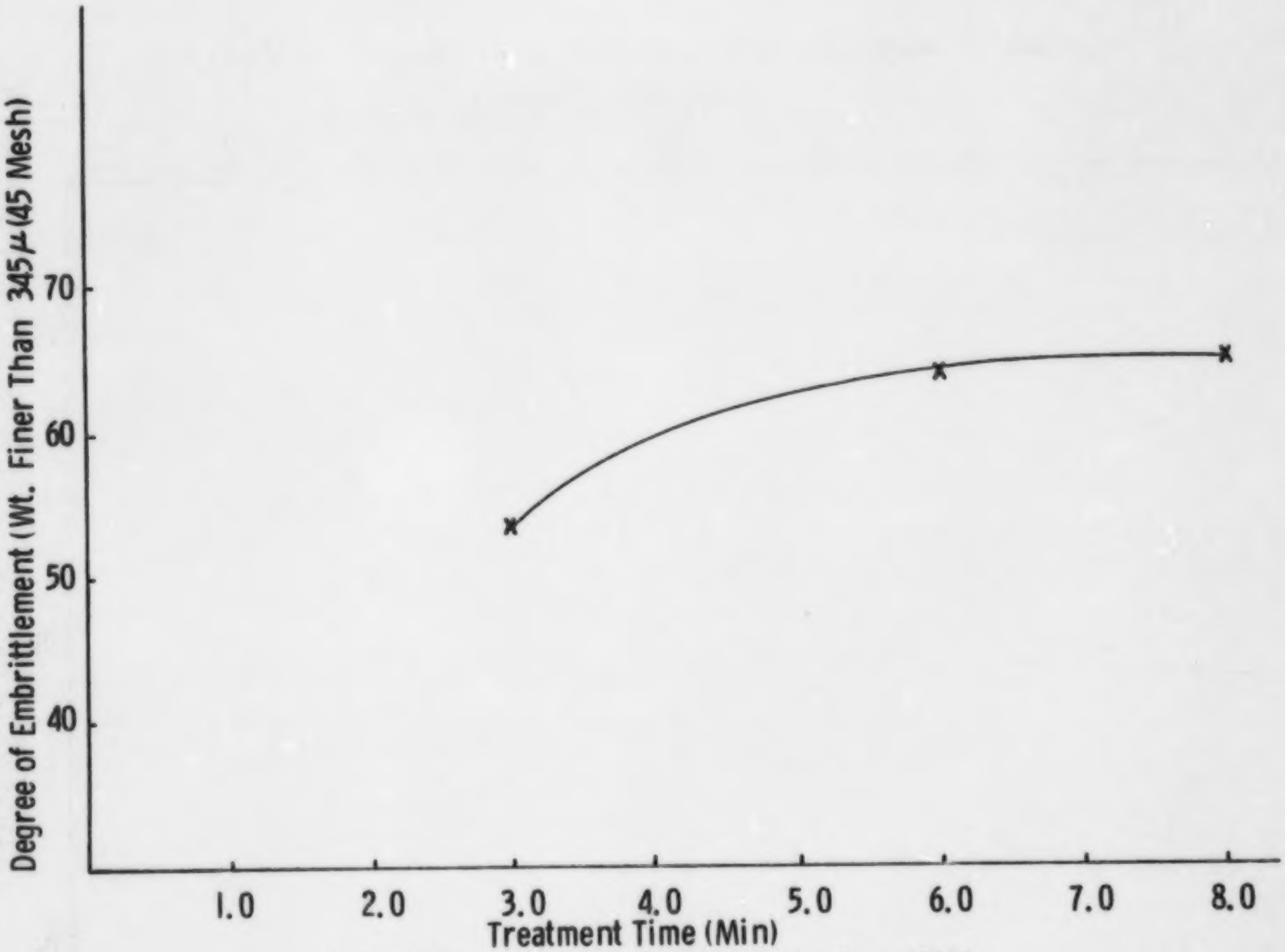


Figure 14. Effects of treatment time (RDF).

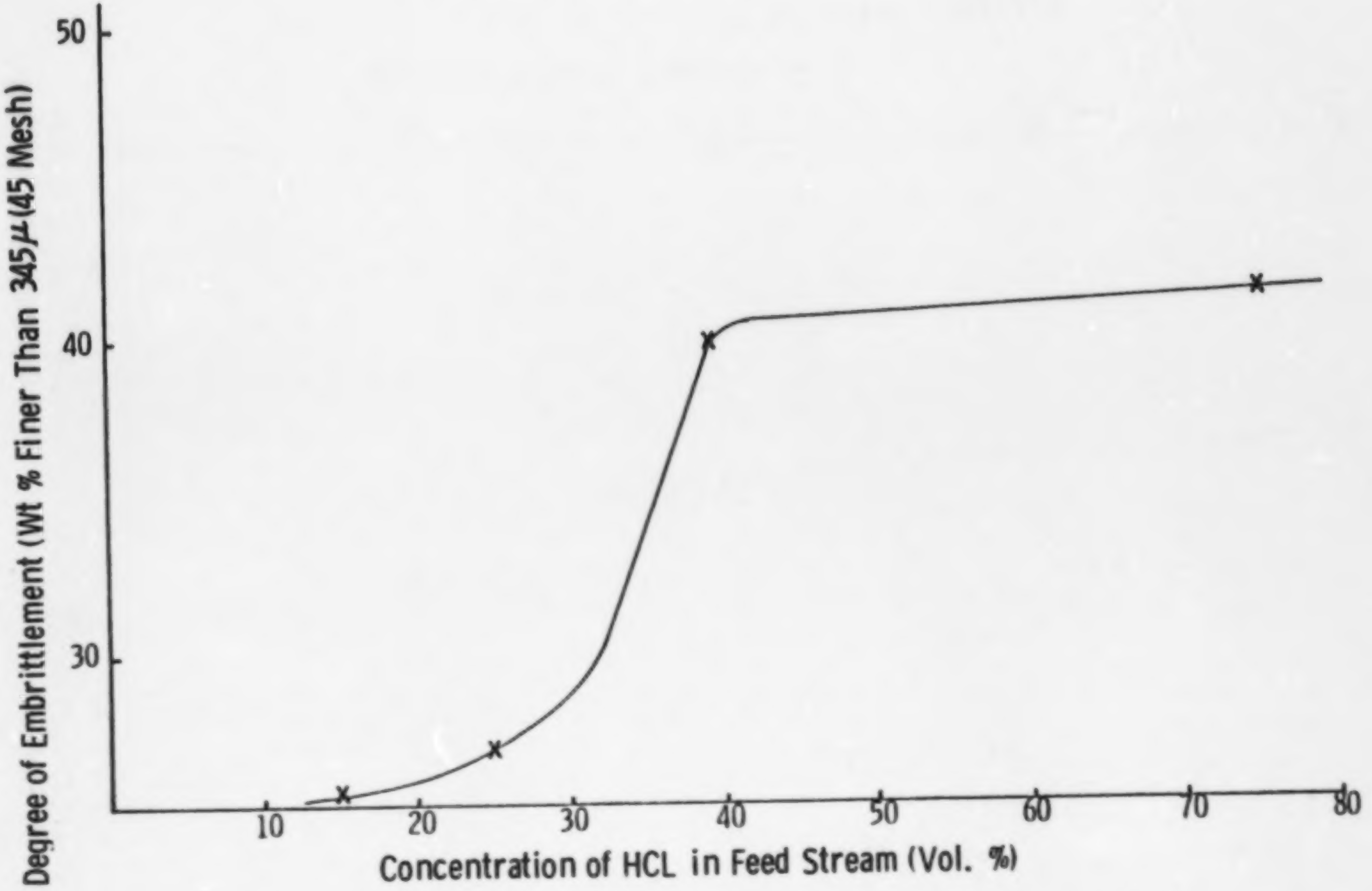


Figure 15. Effect of HCl concentration (shredded newsprint).

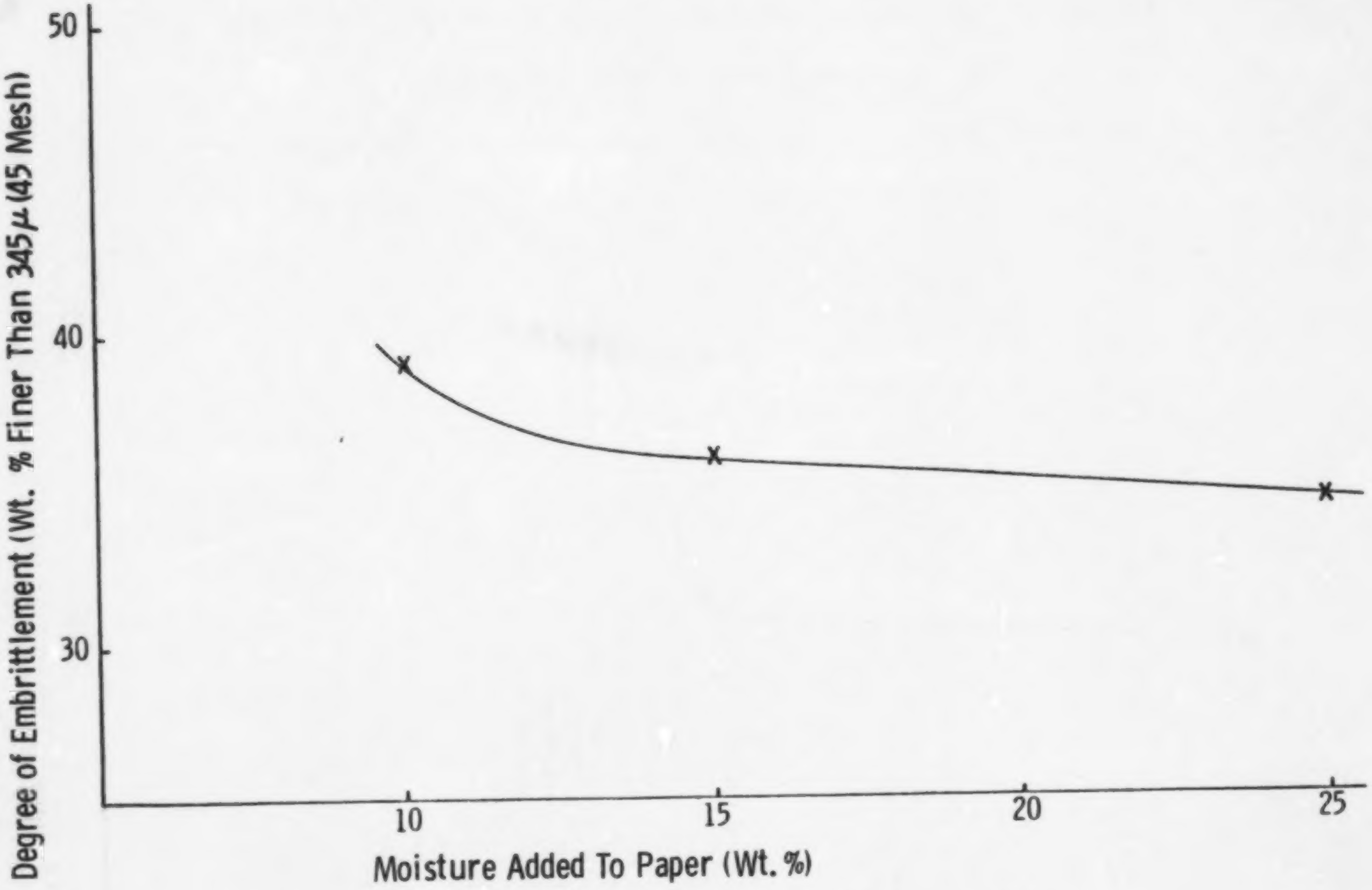


Figure 16. Effect of moisture (shredded newsprint).

(Table 12, Figure 16). Moreover, the retention of HCl is increased, due probably to increased absorption on the moist material. The results from this series of tests demonstrates the need to minimize the moisture content in the cellulose charge. Since shredded waste samples with 40% moisture could not be ball milled, it may be necessary to include provisions for drying the waste in a large scale operation.

The results from the series of tests investigating the effects of sample size showed that when sample size was increased from 1.1 to 2.5 kg (2.5 to 5 lb) for the same HCl concentration and reaction time, the degree of embrittlement dropped significantly (see Table 13 and Figure 17). Considerable improvement in the degree of embrittlement was observed when the reaction time was increased from 3 to 6 min. When both the reaction time and the HCl concentration were increased, the degree of embrittlement was further increased. These results show that there is a definite relationship between the total quantity of HCl required and the amount of sample to be treated. A minimum quantity of HCl per kilogram (pound) of sample must be maintained for the desired degree of embrittlement. The appropriate ratio of HCl to waste will also have to be maintained for all scale-up designs.

In summary, acceptable operating results were obtained at 149°C (300°F), 6-min reaction time, and 50% by volume concentration of HCl in the reactive gas mixture. From preliminary tests conducted, it was concluded that the degree of embrittlement could be improved by raising the treatment temperature to between 177 and 204°C (350 and 400°F) and extending the reaction time to 8 to 10 min. At temperatures above these values, processing problems may be encountered. From the data obtained in these series of experiments, it can be concluded that the degree of embrittlement is maximized at the higher treatment temperatures, longer reaction times, minimum moisture content, and moderate levels of HCl concentration.

ANALYSIS OF REACTOR OPERATIONS

The reactor system shown in Figures 9 and 10 was designed as a pilot unit for embrittlement studies. The materials used for its construction were selected to withstand the anticipated corrosive environment. This system was in use for about 10 months and during this period no serious corrosion damage was observed. However, a few minor corrosion problems were encountered with several components in the system. These problems are discussed below.

Reactor Coating

The Teflon-epoxy coating used for the interior lining of the reactor was recommended by the manufacturer for use to

TABLE 13. EFFECTS OF SAMPLE SIZE (RDF)

Reactor conditions								Product particle size distribution (cumulative % retained)			
Weight of sample [kg (lb)]	Treat. time (min)	Flow rate of HCl [ℓ/min (cfm)]	Flow rate of N_2 [ℓ/min (cfm)]	Concentration of HCl (vol %)	Avg. temp. °C (°F)	Time to temp. (min)	HCl consumed in process g/g+	45 Mesh (354 microns) (wt %)	100 Mesh (140 microns) (wt %)	200 Mesh (74 microns) (wt %)	Pan (wt %)
1.1 (2.5)	3.0	17.6 (.62)	20.4 (.72)	46.3	154.4 (310)	11.1	.029	46.3	55.9	75.7	100
2.3 (5.0)	3.0	17.6 (.62)	20.4 (.72)	46.3	157.8 (316)	10.2	.01	83.5	88.3	93.4	100
2.3 (5.0)	6.0	17.6 (.62)	20.4 (.72)	46.3	153.9 (309)	11.3	.044	55.4	62.9	73.7	100
2.3 (5.0)	6.0	26.3 (.93)	10.2 (.36)	72.1	150.0 (302)	12.5	--	32.1	42.1	63.1	100

+ g HCl/g sample

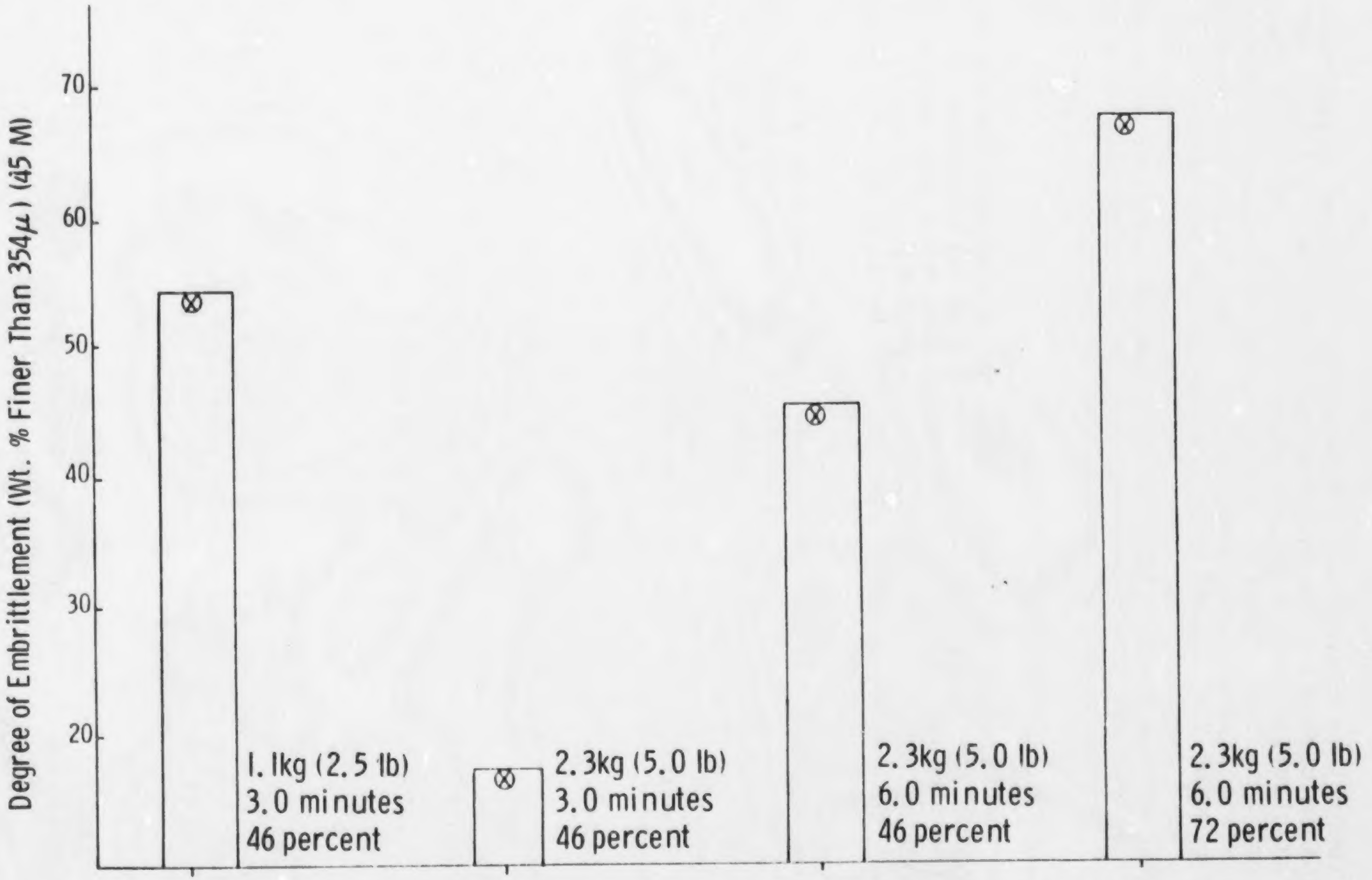


Figure 17. Effects of sample size & HCl concentration (RDF).

260°C (500°F) in corrosive environments. However, approximately half the thickness of the coating was lost after 3 months of operation leaving behind a thin black coating. Although there were some localized flaws in the coating, the reactor did not show any significant corrosion damage. The Teflon coating used on the reactor lid lasted only 2 weeks in the HCl environment and elevated temperatures. The lid was used for 7 additional months after the coating was gone. Although the bare metal lid (carbon steel) was completely exposed to the operating environment, it showed no significant corrosion damage.

Teflon and Silicone Rubber Parts

Teflon fittings exhibited excellent resistance to the HCl environment and operating temperatures with no evidence of corrosion damage. However, a major problem with the Teflon components was their low resistance to mechanical stress. These fittings had to be periodically replaced because of worn threads which resulted in leaks in the system.

Although all the sealing gaskets were made from a high temperature silicone rubber, they had to be replaced about every 3 weeks. Examination of these gaskets showed that the HCl apparently reacted slowly with the rubber in the presence of condensed moisture causing degradation of the rubber and subsequent leaking. Gaskets in the shielded area of the reactor were replaced only once during the entire operating period.

Iron, Aluminum and Monel Parts

The cast iron fittings and other metal parts on the outside of the reactor showed only a moderate degree of uniform corrosion. Cast iron gradually rusts under normal atmospheric conditions according to the following reaction:

$$\mathrm{2Fe + 2H\ O + O \longrightarrow 2Fe(OH)}$$

$$\mathrm{2Fe(OH)\ \ + H\ O + 1/2\ O \longrightarrow 2Fe(OH)}$$

This reaction is pH dependent and the rate increases with decreasing pH. The condensed moisture on the reactor and occasional contact of HCl results in an accelerated rate of corrosion. The stainless steel, gas-distribution screen at the bottom of the reactor showed stress cracking due probably to the interaction of the imposed stress and corrosion reaction. This screen was replaced after 6 months of service.

Considerable flaking was observed on the aluminum plate which was bolted to the front of the stainless steel cabinet for instrument installation. The coupling of two dissimilar metals, the occasional contact with HCl and the formation of a moist dirt film could account for the flaking observed on the aluminum plate. The monel fittings used in the system showed good resistance to the HCl environment and no significant damage to these fittings was observed.

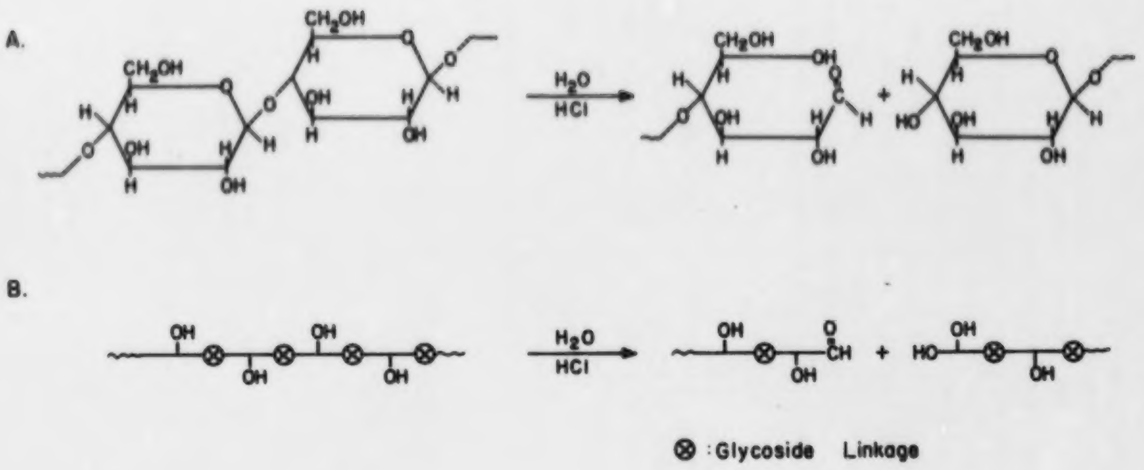
Most of the typical corrosion problems were avoided in the pilot unit by the proper selection of materials and operating procedures. Reactor operating temperature was maintained above the dew point most of the time. In addition, the reactor system was purged with N_2 before the system was shut down. Using these operating procedures, the carbon steel reactor provided satisfactory resistance to corrosion. Experience with this system demonstrated that a large scale reactor could also be constructed from carbon steel provided the operating temperature of the reactor was maintained above the dew point and the system was always flushed to remove residual HCl. Monel could be used for the pipes and fittings, and heating tape could be used to keep the temperature of pipes and fittings above the dew point. Teflon gaskets are also recommended for use in a scaled-up system.

EMBRITTLEMENT MECHANISMS

A number of mechanisms have been considered to account for the embrittlement observed with the treated cellulose samples. It is believed that the embrittlement process is not a single mechanism but rather a complex combination of mechanisms. Both a reduction in the degree of polymerization (DP) and the formation of cross-links between polymer chains are believed to be among the dominant factors for cellulose embrittlement in the presence of a mineral acid.

The acid-catalyzed hydrolysis of cellulose is a well documented reaction, and the selection of HCl was based upon this fact. Using standard procedures (TAPPI T-230), the viscosities of cellulose solutions were measured, and it was confirmed that a reduction of DP occurs for cellulose samples subjected to the embrittlement process. The reaction is shown conventionally in Figure 18A and in a more cryptic but simpler format in Figure 18B. It is believed that the water taking part in the acid hydrolysis reaction is physically adsorbed on the cellulose. Loss of this water of hydration can also contribute to cellulose rigidity.

In an effort to better understand the embrittlement process, several samples of filter paper were exposed to different embrittlement treatment times and then dissolved in cupriethylenediamine. The viscosities of cupriethylenediamine and cupriethylenediamine solutions with treated and untreated filter paper were measured. The results of these tests are compiled in Table 14. The flow times of the solutions are the measure of solution viscosity used for this analysis. The cupriethylenediamine by itself had a flow time of 9.5 sec and in solution



A.
B.
CH₂OH
OH
H
O
HO
H₂O
HCl
CH
⊗ :Glycoside Linkage

Figure 18. Reduction of the degree of polymerization of cellulose by hydrolysis.

TABLE 14. COMPARISON OF EMBRITTLEMENT AND VISCOSITY OF CUPRIETHYLENEDIAMINE SOLUTIONS OF PAPER

Embrittlement Ranking	Sample Designation*	Flow Times (sec) Whatman Paper	 S&S Paper[+]
1	Untreated	270	116
2	LT	22	17
3	MT	17	16
4	IT	17	17
5	HT	12[‡]	12[‡]
-	Cupriethylene-diamine reagent	9.5	

[*] LT-light treatment, MT-moderate treatment, IT-intermediate treatment, HT-heavy treatment.

[+] S&S filter paper obtained from the Schleicher & Schuell Co., New York, NY.

[‡] Incomplete solutions. Approximately 10-40% solids by volume.

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with untreated Whatman and S&S filter paper it had average flow times of 270 sec and 115 sec respectively.

A comparison of solution viscosity and degree of embrittlement for various filter paper samples reveals that there is no simple relationship between these properties. Very mild treatment with HCl results in a filter paper (LT) which is only slightly embrittled yet it yields a solution having a relative viscosity of approximately 10% of that observed for solutions of untreated paper. More extensively treated and embrittled filter papers on the other hand (MT and IT) failed to show significant additional decrease in viscosity. Highly embrittled paper fails to completely dissolve suggesting a high DP, yet the supernatant solutions in these experiments have viscosities which approach that of the pure reagent. Conversations with scientists at the Forest Products Laboratory in Madison and the Paper Institute in Appleton, Wisconsin, had indicated that overpulping (reduction in DP) should result in paper with certain undesirable properties, but brittleness was not one of them. The results shown in Table 14 appear consistent with these predictions. Clearly, the precipitous drop in viscosity for sample LT compared with untreated material indicates a large decrease in DP. Since sample LT is only poorly embrittled, and because the embrittlement changes markedly for the remainder of the samples with little change in viscosity being observed, it is concluded that acid-catalyzed hydrolysis of cellulose is not entirely responsible for embrittlement.

The results of these limited studies were used for formulating a working model for embrittlement. However, the model still requires experimental work for confirmation. It is believed that the lack of total solubility of the highly embrittled sample HT is particularly significant in formulating a mechanism for embrittlement, and we interpret this result as an indication of cross-linking between cellulose chains and/or cellulose oligomers. Assuming that this cross-linking occurs via the formation of ether linkages as shown in Figure 19, the following reactions in the cellulose can be predicted:

1) Rigidization with attendant ease of fracture;
2) Decrease in solubility as the molecular shape changes from a long extended form with readily accessible OH groups to a more spherical form with reduced surface area and inaccessible OH groups;
3) A rapid decrease in molecular weight or DP as the reactive glycoside linkages are cleaved, followed by a slowing of the decrease in DP as cross-linking takes place; and,
4) A decrease in the quantity of retained HCl as the process temperature is increased. The ether cross-links are thought to be formed by the reaction of OH groups with chlorinated cellulose, and the subsequent loss of HCl. Higher process temperatures should lead to more complete cross-linking and loss of HCl.

Further elucidation of the mechanism for HCl-induced embrittlement will require sophisticated instrumental analysis. An attractive but more pragmatic alternative would consist of testing multifunctional cross-linking agents which are less strongly acidic than HCl, but would be expected to induce cross-linking under mild conditions. Reagents such as isocyanates, esters, silanes, etc., could be used for this type of test program.

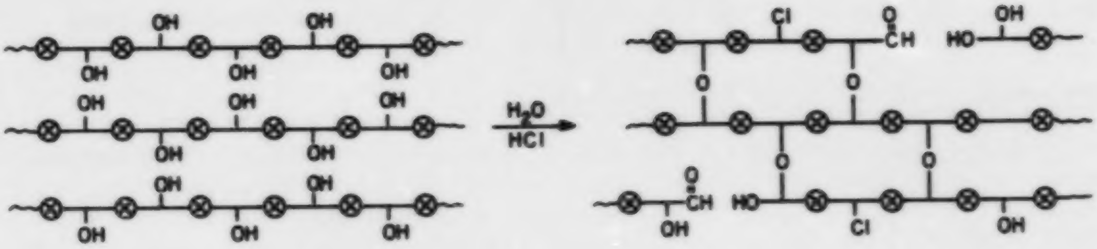
OH
H_2O
HCl
Cl
CH
HO
O

Figure 19. Possible embrittlement mechanism; hydrolysis and crosslinking of adjacent cellulose chains by oxygen bridges.

SECTION 5

ENGINEERING ANALYSIS

PLANT DESIGN

In a third phase of this project a design was developed for a plant to process 907 mt (1000 tons) of refuse per day for the production of powdered cellulose for use as a fuel. The flow plan finally selected is shown in Figure 20. This plan is based on the use of commercially available and proven technology. The basis for the selection of each processing step and item of equipment is described in the following sections.

Trommel - 12.7 cm (5 in) Openings

After the refuse is received and the oversized bulky wastes are removed manually, the solid waste would be processed in a trommel with 12.7 cm (5 in) diameter openings. A trommel was selected as the first processing step to reduce the load to the shredder, remove a majority of the glass and metal, reduce shredder wear, and facilitate metal and glass recovery.

Trommels or rotary screens are one of the major types of processing equipment which can be utilized for recovery of the valuable components in MSW. Although the use of trommels in the mining industry for ore recovery dates back to the early 1800's, they have been replaced in recent years by vibrating screens. At the present time, trommels are used for sizing sand and gravel materials. More recently, they have been tried on a limited scale in some of the solid waste processing facilities (8,9,10).

Trommels are revolving screens consisting of perforated cylindrical tubes mounted on drive units. The trommel is usually mounted on an incline with the feed introduced at the upper end of the tube. The material to be screened then tumbles down the tube. The undersized material passes through the openings in the cylinder wall, while oversized material exits at the lower end of the trommel. The material tends to follow a helical path through the length of the tube. The openings in the trommel can be of a single size or there can be two or three zones of different sized openings. In addition, compound trommels consisting of two or more concentric screening tubes on the same axis can be used for multifraction recovery.

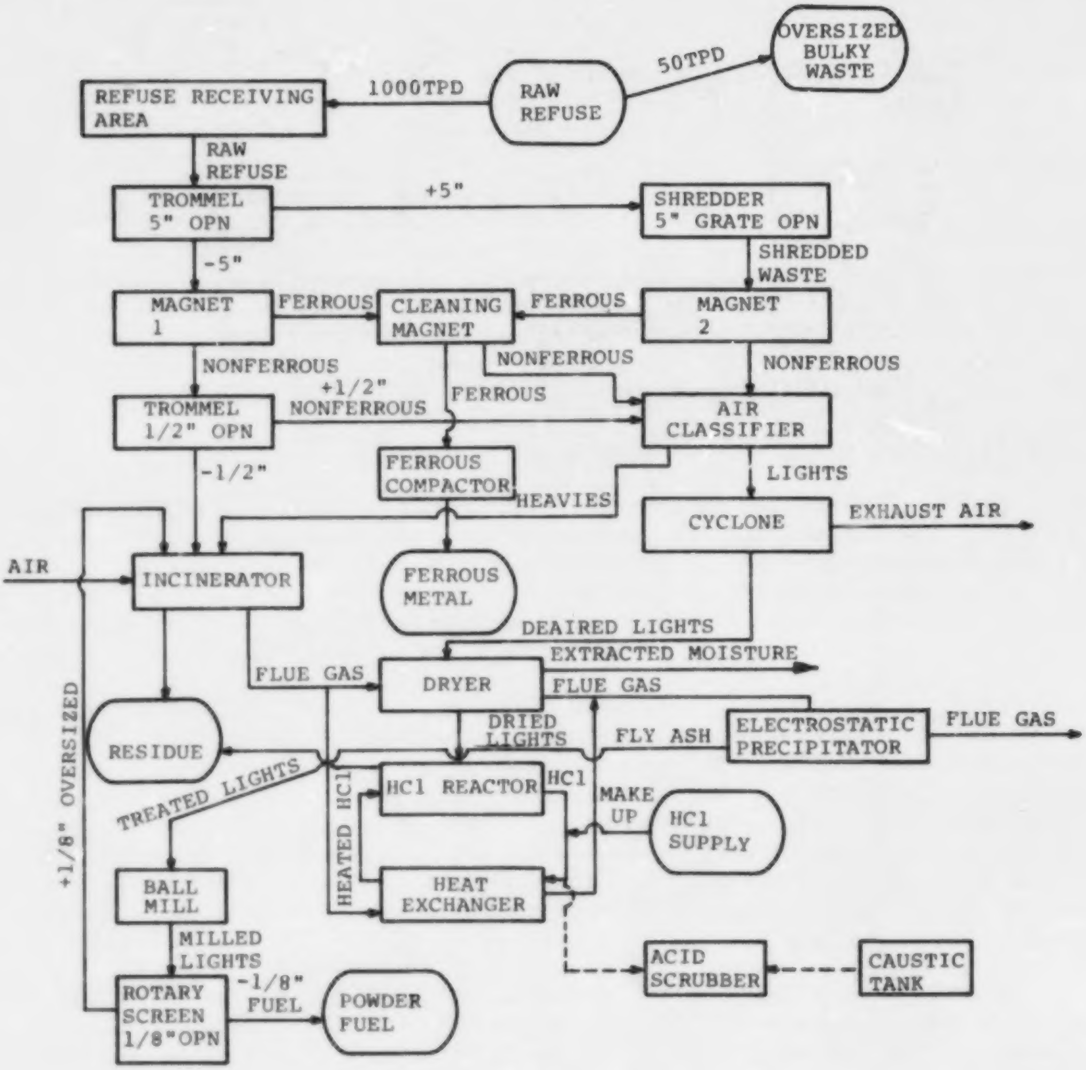
OVERSIZED BULKY WASTE
50TPD
RAW REFUSE
1000TPD
REFUSE RECEIVING AREA
RAW REFUSE
TROMMEL 5" OPN
+5"
SHREDDER 5" GRATE OPN
SHREDDED WASTE
-5"
MAGNET 1
FERROUS
CLEANING MAGNET
FERROUS
MAGNET 2
NONFERROUS
NONFERROUS
NONFERROUS
+1/2" NONFERROUS
FERROUS
TROMMEL 1/2" OPN
AIR CLASSIFIER
-1/2"
FERROUS COMPACTOR
HEAVIES
LIGHTS
CYCLONE
EXHAUST AIR
AIR
INCINERATOR
FERROUS METAL
DEAIRED LIGHTS
EXTRACTED MOISTURE
FLUE GAS
DRYER
FLUE GAS
+1/8" OVERSIZED
RESIDUE
DRIED LIGHTS
FLY ASH
ELECTROSTATIC PRECIPITATOR
FLUE GAS
TREATED LIGHTS
HEATED HCl
HCl REACTOR
HCl
MAKE UP
HCl SUPPLY
BALL MILL
HEAT EXCHANGER
MILLED LIGHTS
ACID SCRUBBER
CAUSTIC TANK
ROTARY SCREEN 1/8"OPN
-1/8" FUEL
POWDER FUEL

Figure 20. Process flow plan (English equivalent)

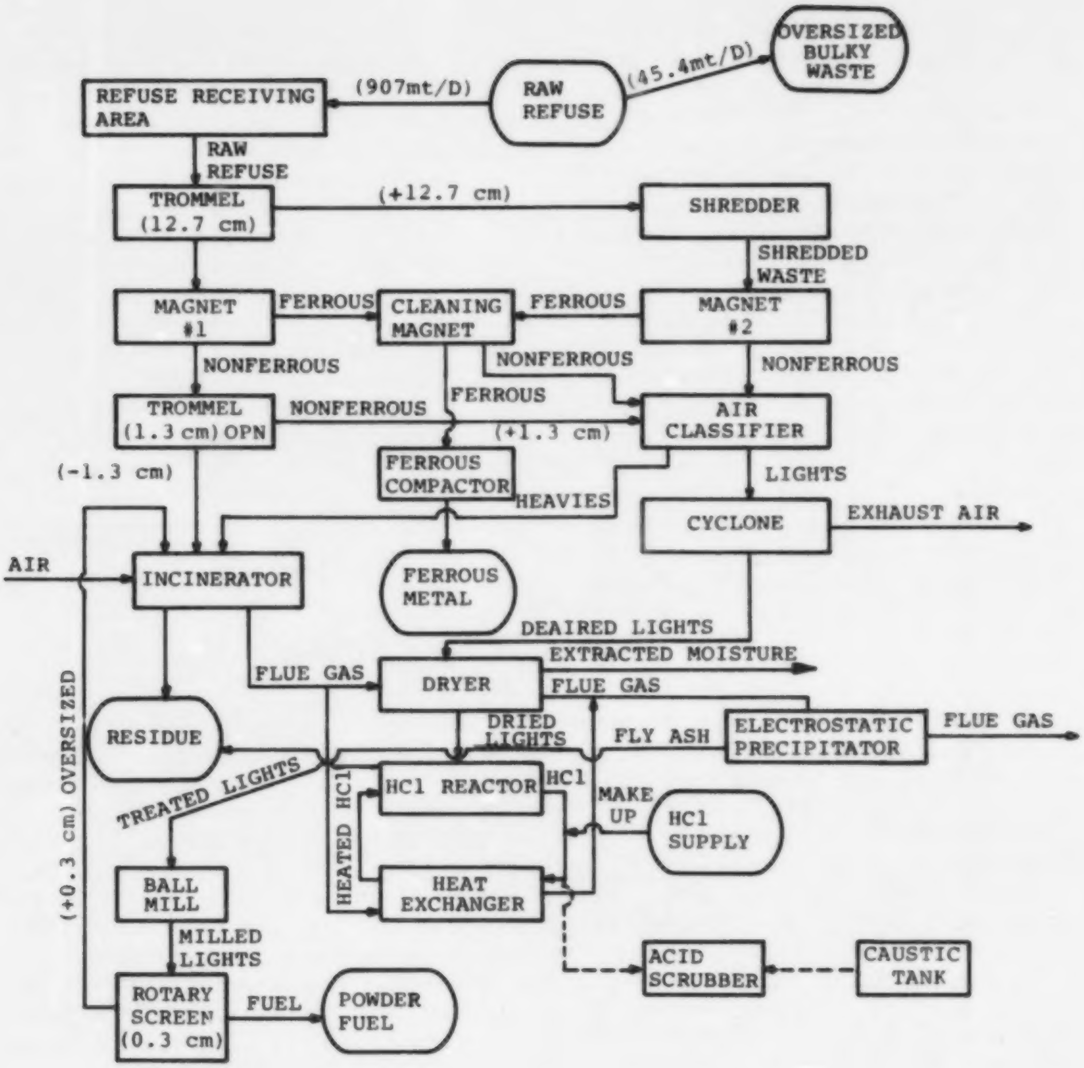
OVERSIZED BULKY WASTE
(45.4mt/D)
RAW REFUSE
(907mt/D)
REFUSE RECEIVING AREA
RAW REFUSE
TROMMEL (12.7 cm)
(+12.7 cm)
SHREDDER
SHREDDED WASTE
MAGNET #1
FERROUS
CLEANING MAGNET
FERROUS
MAGNET #2
NONFERROUS
NONFERROUS
NONFERROUS
FERROUS
TROMMEL (1.3 cm) OPN
NONFERROUS
(+1.3 cm)
AIR CLASSIFIER
(-1.3 cm)
FERROUS COMPACTOR
HEAVIES
LIGHTS
CYCLONE
EXHAUST AIR
AIR
INCINERATOR
FERROUS METAL
DEAIRED LIGHTS
EXTRACTED MOISTURE
FLUE GAS
DRYER
FLUE GAS
(+0.3 cm) OVERSIZED
RESIDUE
DRIED LIGHTS
FLY ASH
ELECTROSTATIC PRECIPITATOR
FLUE GAS
TREATED LIGHTS
HEATED HCl
HCl REACTOR
HCl
MAKE UP
HCl SUPPLY
BALL MILL
HEAT EXCHANGER
MILLED LIGHTS
ACID SCRUBBER
CAUSTIC TANK
ROTARY SCREEN (0.3 cm)
FUEL
POWDER FUEL

Figure 20a. Process flow plan (metric).

Trommels with two or more zones of different sized openings or compound trommels may be very effective in concentrating selected components in municipal solid waste. These units could also provide a means for separating the combustible fraction, or a glass-rich or metal-rich fraction.

The design specification and operating parameters for trommels are dictated by the physical characteristics of the material to be screened, the required feed rate, and the separation requirements. The primary design parameters include trommel length, diameter, slope, and aperture size and array to be utilized. The primary operating parameters are rotation velocity and feed rate. The length of the trommel selected will determine the retention of the material in the unit and affect the screening efficiency. The greater the trommel length, the more complete will be the removal of undersized material; however, the majority of screening occurs in the first few meters (feet) of the unit. For screening raw MSW it must be remembered that a considerable portion of the material will be in plastic or paper sacks, and that in the first few feet of travel the sacks will have to be broken open. Thus, in the initial few meters (feet) of processing only a fraction of the undersized material will come into contact with the openings in the wall of the trommel. For most mineral ore dressing applications, trommel length rarely exceeds 3 to 4.6 m (10 to 15 ft). For screening MSW, trommel length selection will be based upon the nature of the material and the separation efficiency desired. To date this selection has been based mostly on the trial and error method.

The diameter selected for a trommel unit will determine in large part the capacity of the unit and the thickness of the bed during processing. For a fixed feed rate, the larger trommel diameter will result in the thinner bed of refuse. One correlation developed for determining trommel diameter for given capacities is described in Taggart (11) where D (the diameter in inches) is equal to $7.66 \sqrt{C/Gs}$, where C is capacity in tons per hour and Gs is specific gravity of the feed material. For MSW, specific gravity will range from 1 to 1.5. It must be recognized that this formula was developed for the screening of coal, sand, and stone type materials and may not be appropriate for MSW which is not as free flowing a feed material. In addition, an initial process required in the processing of MSW is the breaking open of the plastic and paper sacks, the breaking apart of agglomerates and the breaking of the large glass and ceramics. Trommel diameter and rotating speed must be carefully selected to allow the cascading and cataracting actions to open the bagged and compacted material.

Based on their experience as a manufacturer of screening equipment, Triple/S Dynamics (12) has developed a different approach for determining the diameter to capacity relationship for trommel units processing MSW. Their experience has shown that the best results are obtained when the volume of MSW being processed is about 25% the available volume of the trommel. To calculate the desired diameter, Triple/S Dynamics assumes an average velocity through the trommel of 4.6 m/min (15 ft/min). The resultant formula for determining trommel diameter is then $D = 24 \sqrt{C/2.12}$. Using the formula presented in Taggart and the approach and assumptions developed by Triple/S Dynamics, the diameter to capacity relationships are compared in Table 15.

TABLE 15. COMPARISON OF DIAMETER
TO CAPACITY RELATIONSHIP

Diameter m (in)	Capacity, [mt/hr (tons/hr)] Taggart	Triple/S
.91 (36)	25.4 (28)	4.5 (5)
1.22 (48)	45.4 (50)	8.2 (9)
1.83 (72)	99.8 (110)	17.2 (19)
3.05 (120)	278.5 (307)	48.1 (53)

In New Orleans, a 3 m (10 ft) diameter trommel installed for processing MSW, has reported a feed rate capacity of over 91 mt/hr (100 ton/hr) (13). The data from New Orleans show a capacity almost twice that calculated by the Triple/S approach, and about one-third that calculated by the formula in Taggart.

The slope of the trommel employed will affect the rate at which the material travels through the unit. For a given feed rate, the greater the slope the thinner the bed, thus providing for higher efficiencies of screening. Taggart states that for punch-plate trommels, a slope of 5° is recommended, and for woven-wire units, a slightly greater slope is required. In New Orleans, the slope selected for the trommel unit was 5°. Trommel slopes of 3, 4, and 5° were evaluated in a study for the National Center for Resource Recovery (NCRR) and Tennessee Valley Authority (TVA), and little difference was observed (14,15). At the University of California's Solid Waste Processing Laboratory, Savage and Trezek (16,17) used a trommel with an inclination of 15° to separate the fine fraction from shredded municipal solid waste. For a fixed feed rate, trommel slope and rotation speed have to be properly selected to have effective screening of MSW materials. Trommel rotation speed will also affect both the capacity and efficiency of the trommel unit. As rotating speed increases, trommel efficiency will pass through a maximum and then decrease sharply (11). Maximum efficiency appears to correspond to a rotating speed which causes the load to ride about two-thirds of the way to the top of the screen. The height to which the refuse will travel along the side of the trommel before it tumbles down (cataracting and cascading) is determined by the critical speed for the particular unit. The critical speed, defined by the equation $v_c = 76.6/\sqrt{D}$, where D is the diameter (in ft) of the trommel and v_c is the velocity at which centrifugal force on the waste in contact with the shell at the height of its path equals the force on it due to gravity (18). At speeds greater than v_c the waste would be carried around the shell of the rotating trommel. Rotating speeds will normally range from 35 to 40% of critical velocity (11). For a trommel with a 0.9 m (3 ft) diameter critical speed would be 44.22 rpm; for a trommel with a 1.2 m (4 ft) diameter 38.3 rpm; and for a 1.8 m (6 ft) diameter trommel, 31.2 rpm. In recent studies with trommels processing municipal solid waste, rotational velocities of from 9 to 30 rpm have been reported.

In addition to length and diameter variations, trommels can also be designed with different configurations - cylindrical, conical, or hexagonal. Conical units have been used to a considerable extent in gravel washing plants. Hexagonal trommel units have been used for screening of fine materials. In a study reported by Taggart, a hexagonal unit was compared with a cylindrical unit and found to be more effective for the screening of pulp. The higher efficiency of the hexagonal trommel is attributed to the greater turnover of material as it flows through the unit.

The walls of the trommel can be constructed from wire mesh or can be punched-metal screens. Although punched-plate screens have a longer life and can be prepared with a wide diversity of aperture designs, they have a lower percentage of open area. The opening in the woven-wire screen will either be square or rectangular. In the punched-plate screen the openings could be round (in a straight or staggered array), square, or rectangular (in a straight or staggered array), or oblong (in a straight, staggered, or diagonal array). Taggart describes in detail the correlation between aperture design and the maximum particle size transmitted (11).

Aperture size, spacing, and shape will be dictated by the fraction identified for separation and the feed rate required. Material separation efficiency is a statistical probability function based on the number of collisions of undersized material with the screen openings, and the capacity of the bed for dry screening. For coal, .91 to 1.2 m (3 to 4 ft) of screen surface per ton .9 mt per hr per in (2.54 cm) of aperture is used (11).

The screening efficiency of trommels will vary from 70 to 90% depending on the interaction of many of the variables associated with the process. Effective screening of MSW requires a comprehensive understanding of the relationship between the processed variables and municipal solid waste materials.

The size distribution and shape characteristics of the material to be treated will vary with the composition of the waste. The size range will extend from grains of sand and dirt to the large bulky items of furniture and household appliances. The morphology of these components can also vary greatly; however, the majority of the waste components will be either cylindrical, spherical, or platelike in shape. A comprehensive understanding of the size distribution, fluctuations, and the range of shapes typical of the different components in the waste stream is necessary for the proper design of a trommel unit.

Several studies investigating the size distribution and morphology of raw refuse are reported in the literature. The most extensive appears to be the Ph.D. thesis by J. Ruf (19). The cumulative distribution curves and the frequency distribution curves (Figures 21 and 22) for the particle size of components in raw refuse developed by Ruf provides a fairly comprehensive evaluation of size distribution. From the data in these curves, which appear to be in good agreement with other published data, it is possible to determine the average component split of raw refuse which might be obtained for different screening processes. Assuming an optimistic 90% screening efficiency the distribution which could be obtained for screening with a trommel having 12.7 cm (5 in) diameter openings is shown in Table 16.

Shredder

The oversized raw refuse from the trommel would be processed in a coarse shredder with grate openings spaced at 12.7 cm (5 in). The coarse shredder was selected to provide size reduction and homogenization of the oversized refuse from the trommel.

A wide range of equipment is available for reducing the size of the received refuse to facilitate more efficient separation and recovery processes. The processes employed include impacting, shearing, tearing, grinding, milling, shredding, pulverizing, and flailing. Shredding is the most commonly used term and is applied to the mechanical processes which reduce the size and homogenizes the refuse. The majority of processes utilize either a grinding action or an impacting action to reduce the refuse. However, both tearing and shredding are likely to occur in combination with the grinding or impacting action. Hammermills and ring grinders are the most commonly used equipment for dry size reduction of refuse.

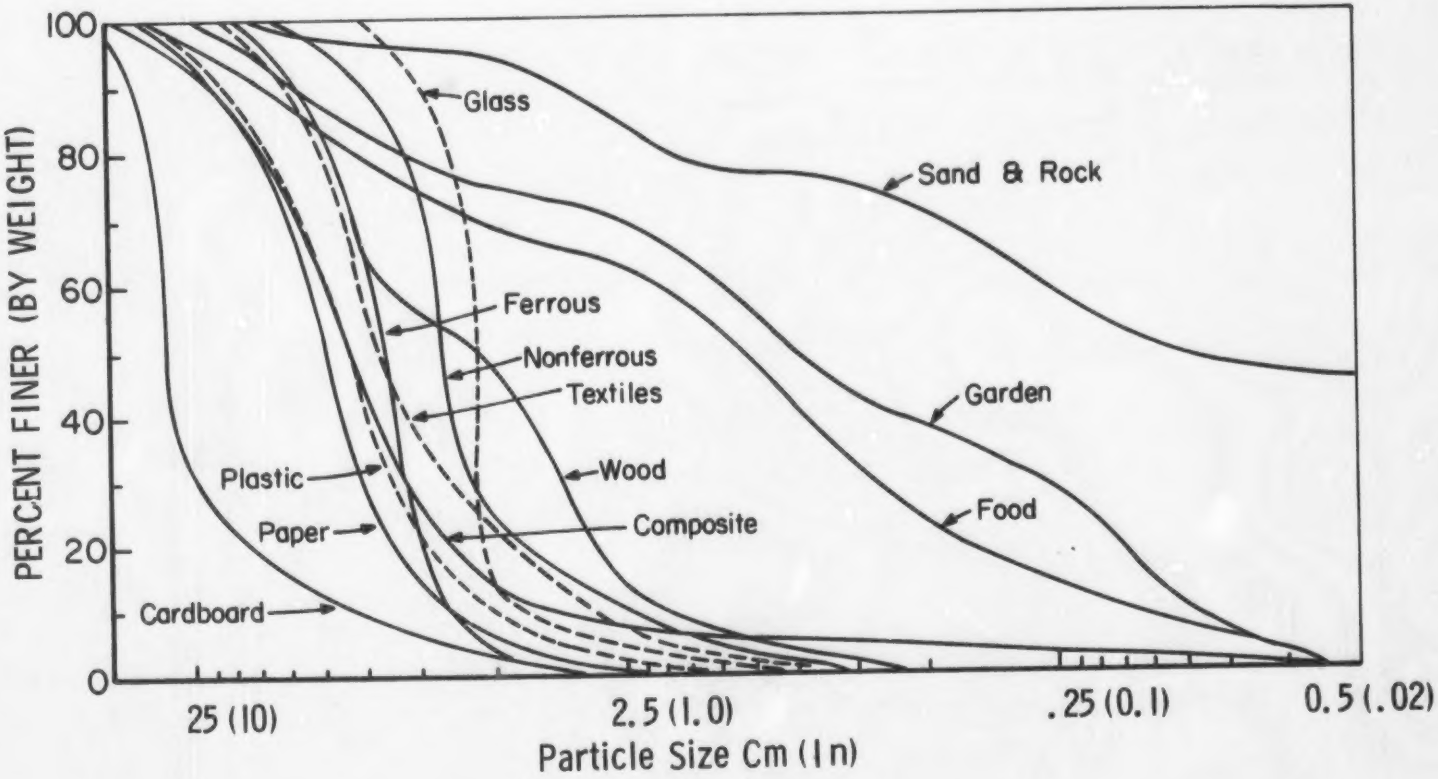

Figure 21. Cumulative distributions of raw waste.

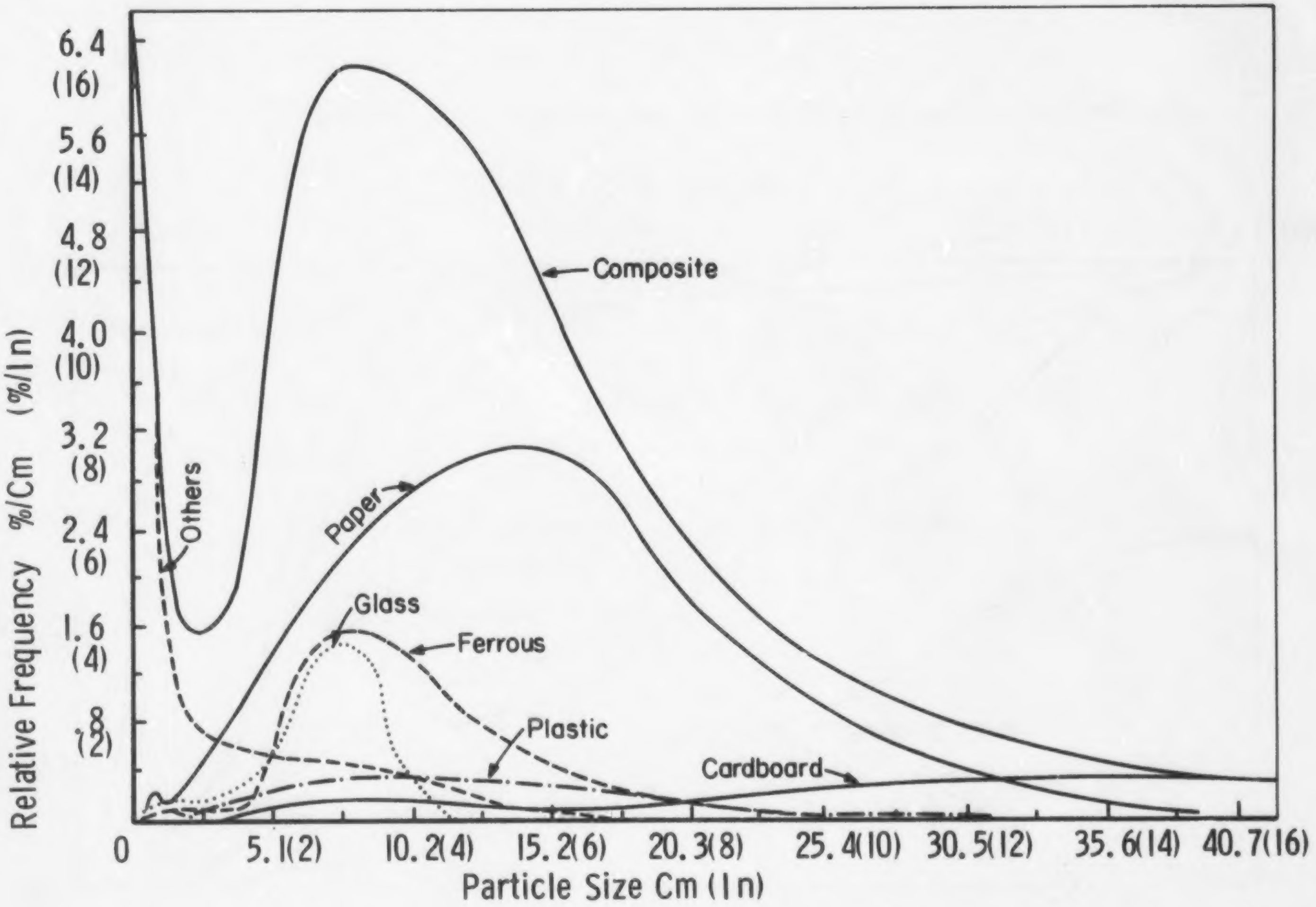

Figure 22. Particle size distributions of raw refuse components.

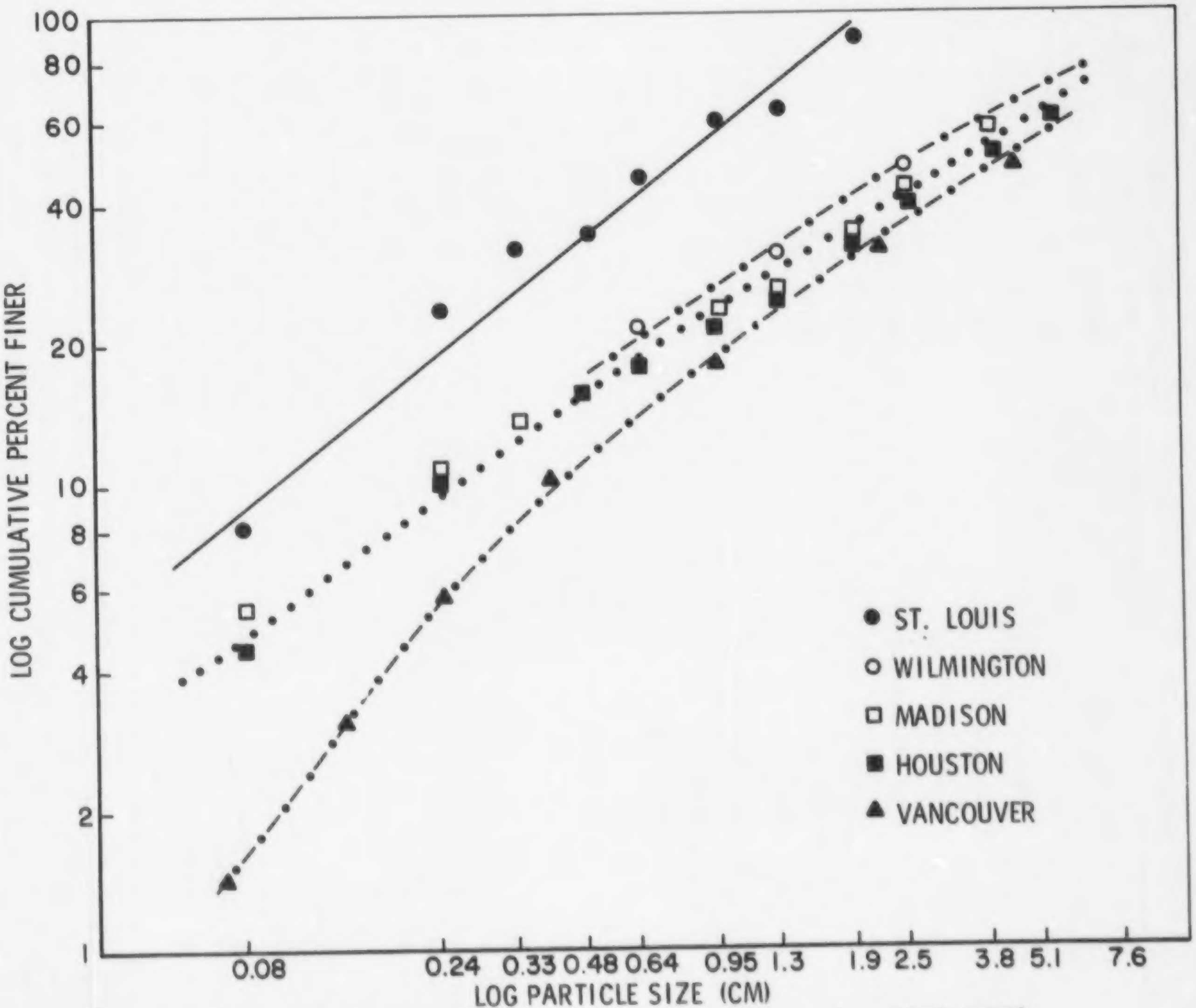

Figure 23. Particle size distribution - shredded MSW*

TABLE 16. DISTRIBUTION OF WASTE COMPONENTS MINUS 12.7 cm (5 in)*

Components	Distribution (%)
Cardboard	10.8
Paper	45
Plastic	55.8
Textile	72
Ferrous	76.5
Non-Ferrous	86.4
Wood	76.5
Food	76.5
Yard	79.2
Sand and Rock	87.3
Glass	90
Composite	55.8

* Estimated distribution recovered assuming 90% screening efficiency.

Flail mills have also been used to a limited extent for shredding refuse. In the flail mill, two sets of articulated flails on parallel shafts are rotated in opposite directions. The flails tear the refuse as it passes between the rotors. This equipment can process large quantities of refuse at very low power levels. The low power requirements are due to the fact that the items difficult to shred (auto tires, metal appliances, etc.) are passed through the machine without being significantly reduced in size. In this kind of system, refuse size is difficult to control; and, this hampers subsequent processing steps. Because of this inability to effectively control particle size of the shredded refuse, the flail mill (a low horsepower shredder) was not selected.

A horizontal hammermill was selected for the proposed plant. These mills must be capable of processing both the normal municipal refuse (residential, commercial, institutional), as well as the occasional bulky items such as household appliances (washing machines, refrigerators, etc.), demolition waste (2x4's, concrete rubble, etc.), automobile tires, water heaters, tree limbs, furniture, etc. These primary shredders should reduce all refuse to less than 12.7 cm (5 in) with 75% less than 10.2 cm (4 in). The hammermills should also have the ability to reject (without being damaged) unshreddable items such as hardened steel shafts and gears.

The particle size distribution of the shredded refuse is quite variable and will be a function of the refuse composition, the feed rate, the size of the exit grate in the hammermill and the weight and speed of the rotating hammers. Shredded municipal refuse from five different sites was obtained by the National Center for Resource Recovery (NCRR). A plot of the data reported is presented in Figure 23. In the hammermill, the metal will be mostly sliced and crumpled, the paper and wood products shredded, and the glass and ceramics pulverized. Because of its friable nature, nearly all the glass and ceramic material will be reduced to particles smaller than 1.3 cm (0.5 in) and the majority smaller than 0.5 cm (0.31 in). A compilation of the glass particles size distribution after primary shredding is presented in Table 17.

The particle size distribution data compiled by NCRR (Figure 23) are based on only several hundred kilograms (pounds) of samples collected during a one-day test period at each facility. Accordingly, more comprehensive data are required about the particle size distribution of municipal refuse shredded in a horizontal hammermill. However, using the data supplied by NCRR as a guide, it would appear that about 25 to 30% of the shredded refuse is minus 1.3 cm (1/2 in) and that the mean particle size is approximately 5.1 cm (2 in). The size distribution data supplied by Williams Patent Crusher and Pulverizer Company for shredded municipal refuse through a 12.7 cm (5 in) cage bar opening is compiled in Table 18. The data provided by Williams appears to be in agreement with the NCRR data.

In his thesis (19), J. Ruf also investigated the size distribution of primary shredded waste components. The cumulative distribution curve and frequency distribution curve obtained by Ruf for the range of components in primary shredded solid waste is shown in Figures 24 and 25. These data appear to be in agreement with the other published data.

Magnetic Separator

The raw refuse passing through the 12.7 cm (5 in) openings in the trommel and the shredded refuse would then be processed at a magnetic separator for ferrous recovery. Two types of magnetic separators are commonly used in these applications: an overhead suspended belt magnet, and a drum magnet. The magnet manufacturers recommend that when either of the magnets is used, it be suspended over the discharge of the conveyor within 20 to 30 cm (8 to 12 in) of the flowing refuse. They further recomment that the refuse conveyor be traveling at speeds up to 120 m/min (400 ft/min) in order to achieve a minimal bed depth 2.5 to 7.5 cm (1-3 in). A cleaner ferrous

TABLE 17. TYPICAL GLASS PARTICLE SIZE DISTRIBUTION*

Opening size cm	(in)	Cumulative % passing
2.5	(1)	100.0
1.9	(3/4)	99.5
1.3	(1/2)	98.5
0.9	(3/8)	91.1
0.6	(1/4)	76.9
0.5	(3/16)	64.8
0.4	(0.14)	54.3
0.2	(0.06)	26.4
0.1	(0.04)	20.6
0.07	(0.03)	15.3
0.05	(0.02)	10.0

* NCRR private communication (1974).

TABLE 18. SIZE DISTRIBUTION WITH A WILLIAMS MILL*

Opening size cm	(in)	Cumulative % passing
15.2	(6)	90
12.7	(5)	80
10.2	(4)	75
7.6	(3)	65
5.1	(2)	52
3.8	(1-1/2)	44
2.5	(1)	32
1.9	(3/4)	27
1.3	(1/2)	20
0.9	(3/8)	15
0.6	(1/4)	13

* Private communications from Williams Patent Crusher and Pulverizer Company (1974).

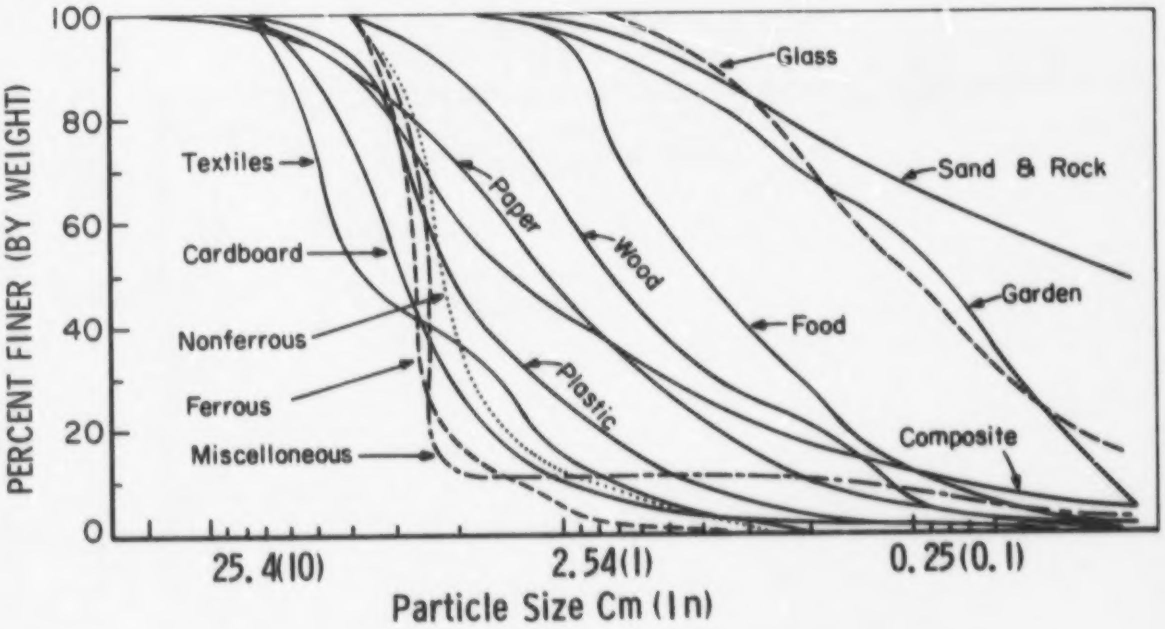

Figure 24. Cumulative distributions of shredded waste.

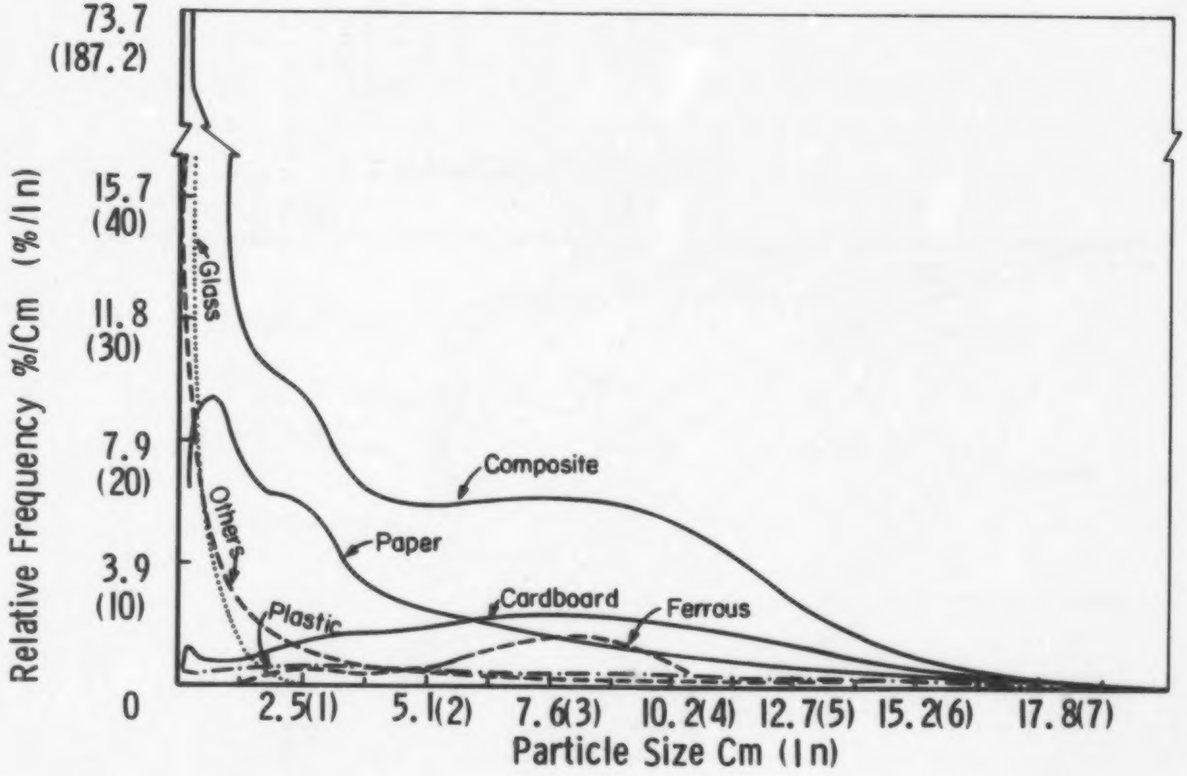

Figure 25. Particle size distributions of shredded waste.

fraction has been reported for the self-cleaning belt magnet unit compared with the drum magnet unit. However, the belt wear is quite high, resulting in excessive maintenance costs. Drum magnets require little maintenance, except for the jamming problems which can be caused by springs and other bulk metal catching between the conveyor and drum.

Although the amount of ferrous metal in the refuse is variable, an average value of 7.5% has been established for the ferrous fraction. It is anticipated that about 80 to 85% of the ferrous metal is removed in the initial magnetic separation phase. The major components of the ferrous fraction are the tin-coated cans, the bimetal tin-coated cans, and the tin-free bimetal cans. These cans represent 60 to 90% of the ferrous fraction. Wire; bottle and jar caps; metal ends from paper containers; metal from cookware, hardware, and appliances; and ferrous metal furniture are the other types of ferrous scrap found in refuse.

The Bureau of Mines (20) sampled some 2.7 mt (6000 lb) of municipal refuse and reported the distribution as shown in Table 19 for the ferrous fraction. In the Bureau of Mines magnetic process, about 3.5% paper was found trapped with the recovered metal. This does not include the paper labels on the cans nor the food wastes and other contaminants trapped in the shredded cans. Total contaminants in the recovered ferrous fraction are likely to range from 5 to 15%.

The ferrous fraction from the primary magnet is conveyed to a cleaning magnet. This final magnetic separation stage is designed to provide a cleaner ferrous fraction for recovery. The material is conveyed to the drum and the nonferrous materials drop past the drum to an outfeed conveyor. An aspiration system can be incorporated with the drum magnet as an option to pull off the light nonferrous fraction. The ferrous fraction picked up by the magnet is conveyed to a ferrous compactor for densification (minimill). Ferrous metal having a density of 561 kg/m^3 (35 lb/ft^3) is compacted to about 1,202 kg/m^3 (75 lb/ft^3) for transport to a ferrous processing plant.

Trommel - 1.3 cm (1/2 in) Openings

The nonmagnetic material from the magnetic separator processing the minus 12.7 cm (5 in) material from the trommel will be processed in a trommel with 1.3 cm (1/2 in) diameter openings. The fine glass, ceramic, and stone particles tend to get carried with the air-classified light fraction that is to be used for fuel. These particles, when in the fuel fraction, can cause erosion problems in the pneumatic transport system and add to the ash and slagging problems in the boiler. It is, therefore, desirable to remove these fines from the refuse.

TABLE 19. DISTRIBUTION OF MATERIALS
IN THE FERROUS FRACTION*

	Percent
Tin-coated cans	56
Bimetal tin-coated cans	17
Bimetal tin-free cans	12
Bottle and jar caps	2
Metal ends from paper containers	1-1/4
Miscellaneous light metal (pins, nails, wire, etc.)	7-3/4
Miscellaneous heavy metal (appliances, furniture, etc.)	4

* Ferrous fraction approximately 7.5% of raw refuse.

A trommel 9.1 to 10.7 m (30 to 35 ft) in length with 1.3 cm (1/2 in) diameter openings should facilitate the removal of the fines in the unshredded refuse. A vibrating flat screen could also be used for this application; however, it is more susceptible to jamming.

An estimated compilation of the waste component size distribution for the minus 1.3 cm (1/2 in) fraction that can be obtained from the raw refuse is presented in Table 20. Assuming 90% screening efficiency the distribution which could be obtained for screening with a trommel having 1.3 cm (1/2 in) diameter openings is shown in Table 20.*

Air Classification

The oversized refuse from the trommel, the nonferrous from the shredder and from the cleaning magnet are to be conveyed to the air classification system for recovery of most of the organic materials.

Air classification is the term used to describe a number of processes which utilize gravity and air currents for material separation. The three main factors that affect the separation of particles in an air stream are particle size, shape, and specific gravity. Vertical, horizontal, and inclined column separator designs have been developed which utilize these parameters to separate the different fractions in solid waste (21). Component density is the major factor for component separation by gravitational processes. A compilation of waste component densities is presented in Table 21.

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* Tables 21 and 22 are based on data in Figures 24 and 25.

TABLE 20. CUMULATIVE SIZE DISTRIBUTION OF WASTE COMPONENTS MINUS 1.3 cm (1/2 in)

Components	Distribution for raw refuse (%)	
Cardboard	Negligible	(0)
Garden	57	(51)
Paper	Negligible	(0)
Food	48	(43)
Plastic	1	(.9)
Ferrous	Negligible	(0)
Textile	1	(.9)
Nonferrous	4	(3.6)
Wood	6	(5)
Glass	1	(.9)
Sand and Rock	79	(71)
Miscellaneous	--	--
Composite	6	

NOTE: Number in parentheses is the estimated screening distribution assumint 90% efficiency.

TABLE 21. WASTE COMPONENT DENSITIES

Component	Density [kg/m^3 (lb/ft^3)]	
Paper	705-1201.5	(44-75)
Plastic	897-1602	(56-100)
Wood	304-897	(19-56)
Aluminum	2675	(167)
Iron	7866	(491)
Rubber and Leather	993-2002	(62-125)
Food and Yard Wastes	721	(45)
Other Nonferrous Metal	8811	(550)
Glass	2307-2996	(144-187)

To suspend a particle in an air stream, the drag must equal the weight:

$$\text{Weight} = \text{Drag}$$

$$V_s \rho_s g = \frac{1}{2} \rho_a C_D v_a^2 S_s$$

where

V_s = Volume of the material
ρ_s = Density of the material
S_s = Surface area of the material exposed to the air stream (lift area)
ρ_a = Density of the air
C_D = Drag coefficient for the material
v_a = Air stream velocity
g = Gravitational force.

By rearrangement:

$$\frac{\rho_a v_a^2}{2g} = \frac{\rho_s V_s}{C_D S_s}$$

If we assume that most shredded waste is "plate-like" then:

$$\frac{\rho_a v_a^2}{2g} = \frac{\rho_s t_s}{C_D}$$

where t_s = average plate thickness

The quantity $\frac{\rho_a v_a^2}{2g}$ can for a constant air stream velocity be considered the levitating parameter (L) against which the different materials in the waste stream can be evaluated:

$$L = \frac{\rho_s t_s}{C_D}$$

A tabulation of the quantity $\rho_s t_s$ for a number of the components in solid waste is presented in Table 22.

To obtain the values shown in Table 22 an average thickness was assumed; however, the thickness of materials in waste have a considerable range which will cause substantial overlap for the different material fractions. This overlap will make complete separation of different fractions by air classification more difficult. It should also be recognized that these calculations assume a constant drag coefficient, this is not likely to be the case. Unfortunately, drag coefficient data

TABLE 22. $\rho_s t_s$ FOR WASTE COMPONENTS

Component	ρ_s Density [g/cm^3 (lb/in^3)]	ts Average thickness [cm (in)]	$\rho_s t_s$ [kg/m^3 (lb/in^2)]
Glass	2.5 (0.0897)	31.1 (0.125)	7.9 (0.0112)
Paper	0.95 (0.0345)	4.1 (0.016)	0.4 (0.0006)
Leather	1.4 (0.0521)	16.0 (0.063)	2.3 (0.0033)
Food and yard wastes	0.7 (0.0260)	16.0 (0.063)	1.1 (0.0016)
Plastics	.12 (0.0434)	4.1 (0.016)	0.5 (0.0007)
Wood	0.6 (0.0231)	63.5 (0.250)	4.1 (0.0058)
Aluminum	2.7 (0.0966)	7.9 (0.031)	2.1 (0.0030)
Iron	7.9 (0.2841)	7.9 (0.031)	6.2 (0.0088)

for waste components are very limited or almost nonexistent.

Both horizontal and vertical classifiers are available for the dry separation of refuse. In the vertical units the upward flow of air in the enclosed column picks up and carries the lower density materials as it contacts the downward falling refuse. Air stream velocity will dictate the separation ratio (light versus heavies). This separation is predominantly a function of the density and surface area of the shredded refuse particles. To compensate for the day-to-day variations in particle moisture content and morphology, a variable air velocity control is necessary.

At the present time two types of vertical classification units are on the market. One of the systems incorporates a zig-zag design in which the bulk shredded refuse is introduced into a vertical air stream as it tumbles down the zig-zag baffles. Each zig-zag provides an additional point of decision for the separation since each zig-zag is a point of turbulence in the air stream. The tumbling action at these points causes the agglomerated materials to be broken up. The second type of unit is essentially a vertical column in which the shredded refuse is injected midway into the column, which has an upward air stream. The column can be rectangular or cylindrical and it may contain baffles that can be tilted. These vertical column units require more closely sized refuse than do the zig-zag units. Manufacturer specifications require that the refuse be minus 3.2 cm (1-1/2 in) in size.

Several types of inclined and horizontal air classifiers have also been developed. In the horizontal unit the shredded refuse is introduced into a horizontal air stream and the refuse particles, as a function of their weight and shape, will drop out of the air stream at different points along the flow path. In most designs, bins are placed under the drop zones, and the very light material is carried out of the classifier with the air stream. In the horizontal system, two to five separate fractions can be recovered depending on the design. The refuse can be introduced into the classifier by dropping it past a horizontal air stream or with a ballistic wheel which hurls the refuse into the horizontal air stream. Designs employing a rotating inclined cylinder have also been developed to classify municipal refuse. In these systems, lifters within the cylinder cause the refuse to cascade down the tube as an upward air flow carries the lights out of the unit, while the heavy fraction is discharged out of the bottom of the cylinder.

Another type of horizontal unit is a vibro-aspirator based on the modification of a gravity or air table. In a vibro-aspirator the shredded refuse is conveyed down a series of stepped vibrating pans. At each step, air passes through the material carrying off the light particles.

The light fraction from the air classifier is pneumatically conveyed to a cyclone for deairing. A cyclone is primarily a settling chamber in which gravitational acceleration is replaced by centrifugal acceleration. (Cyclone design is based on the vortex principle.) The solid gas mixture enters tangentially near the top and is forced down in an ever-decreasing spiral to the solids outlet trap. The solid material drops out of the gas stream in increasing quantities as the apex of the cone of the cyclone is approached. The gas forms a vortex in the center and travels upward into the air outlet. The finer dust particles are usually carried out with the gas and a dust filter is usually required. The light fraction would then be dried and prepared for embrittlement.

Drying

The air classified light fraction is to be dried prior to the embrittlement treatment. The moisture content of municipal refuse is quite variable. Fluctuations between 15 and 50 weight percent of the refuse have been reported with the average being about 30. The air classified light fraction has a moisture content ranging from 20 to 25%. This high moisture content inhibits refuse separation processes and reduces BTU content. For the acid embrittlement process with HCl it is desirable to minimize the moisture content in the waste. Furthermore, the large variation in moisture content from day to day adversely affects the commercial marketability of the organic fraction for use as a fuel. It, therefore, would be desirable to dry the refuse as part of the resource recovery processing.

A number of different drying processes were investigated to determine their applicability for use with refuse. Freeze drying, vacuum drying, chemical drying, hot gas drying, and steam drying processes were considered. Inquiries quickly showed that both freeze drying and vacuum drying are prohibitively expensive. Several different chemical drying techniques have been developed in the laboratory; however, they are not commercially available for large facilities due to their high cost. Dessicants and chemicals forming a hydraulic reaction with water have been used for moisture absorption and removal in the laboratory; however, they are expensive and would be difficult to separate from the refuse after they are employed. It would appear that for the processes considered, hot gas drying or steam heating are the most practical means for removing the moisture from the refuse (22).

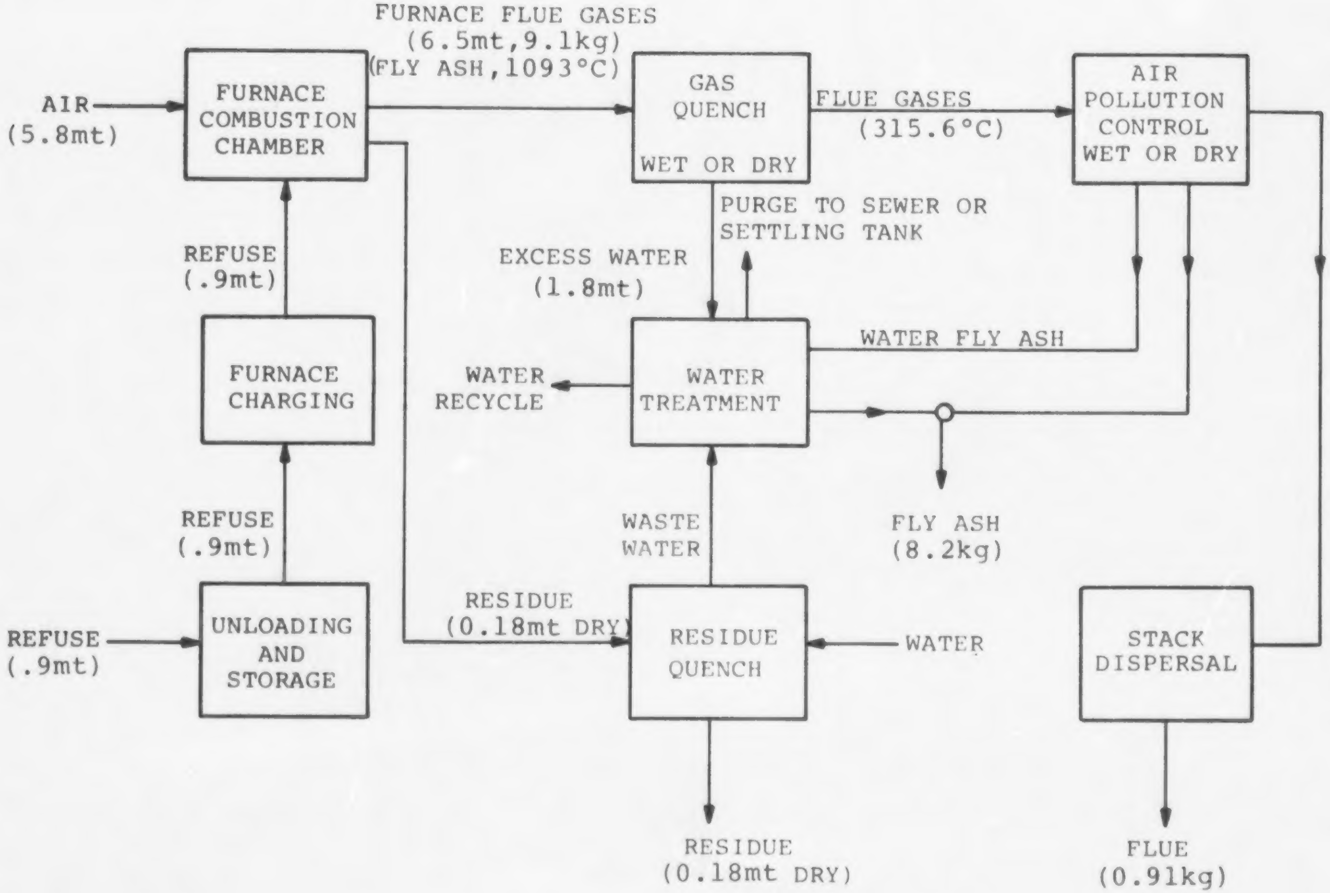
Both direct and indirect dryers can be used for moisture removal from the waste. Indirect heat dryers heat the waste by radiation while direct heat dryers bring the waste into direct contact with a drying medium. A drying medium can be hot air, steam, or hot exhaust gases from a combustion process. For this proposed plan an indirect heated rotary dryer using the hot flue gases coming from an incineration unit would be used. In addition some of the hot flue gases would be diverted to a heat exchanger to heat the HCl going to the reactor.

Incineration and Flue Gas Cleaning (Electrostatic Precipitators)

The heavy fraction from the air classifier, the minus 1.3 cm (1/2 in) fraction from the trommel and the oversized [+0.3 cm (+1/8 in)] from the rotary screen are to be incinerated. The hot flue gases from the incinerator will be used as the heat source for the rotary dryers.

Incineration is the general term applied to a variety of combustion processes used for volume reduction of wastes. The basic components of an incinerator are shown schematically in Figure 26. Incinerators operate on a continuous and/or periodic batch basis. Continuous feed incinerators, e.g., the traveling-grate, reciprocating-grate, ram-feed, and rotary-kiln are more commonly used for incineration of municipal waste. Instead of quenching the flue gases as shown in Figure 26, the heat can be recovered for steam generation. A water wall system can be used in place of refractories in the combustion chember, or a boiler unit can be located after the combustion chamber for heat recovery.

In most of the systems described in the literature, the refuse is received in a storage pit and transferred to the incinerator by an overheated crane and clamshell grab. The crane and grab can be operated at the crane or from a remote station.


FURNACE FLUE GASES
(6.5mt,9.1kg)
(FLY ASH,1093°C)
AIR
(5.8mt)
FURNACE COMBUSTION CHAMBER
GAS QUENCH
WET OR DRY
FLUE GASES
(315.6°C)
AIR POLLUTION CONTROL WET OR DRY
REFUSE
(.9mt)
PURGE TO SEWER OR SETTLING TANK
EXCESS WATER
(1.8mt)
FURNACE CHARGING
WATER RECYCLE
WATER TREATMENT
WATER FLY ASH
REFUSE
(.9mt)
WASTE WATER
FLY ASH
(8.2kg)
RESIDUE
(0.18mt DRY)
REFUSE
(.9mt)
UNLOADING AND STORAGE
RESIDUE QUENCH
WATER
STACK DISPERSAL
RESIDUE
(0.18mt DRY)
FLUE
(0.91kg)

NOTE: Quantities in parentheses are rough measures of flow rates and temperatures.

Figure 26a. Basic Components of an Incinerator - metric units.

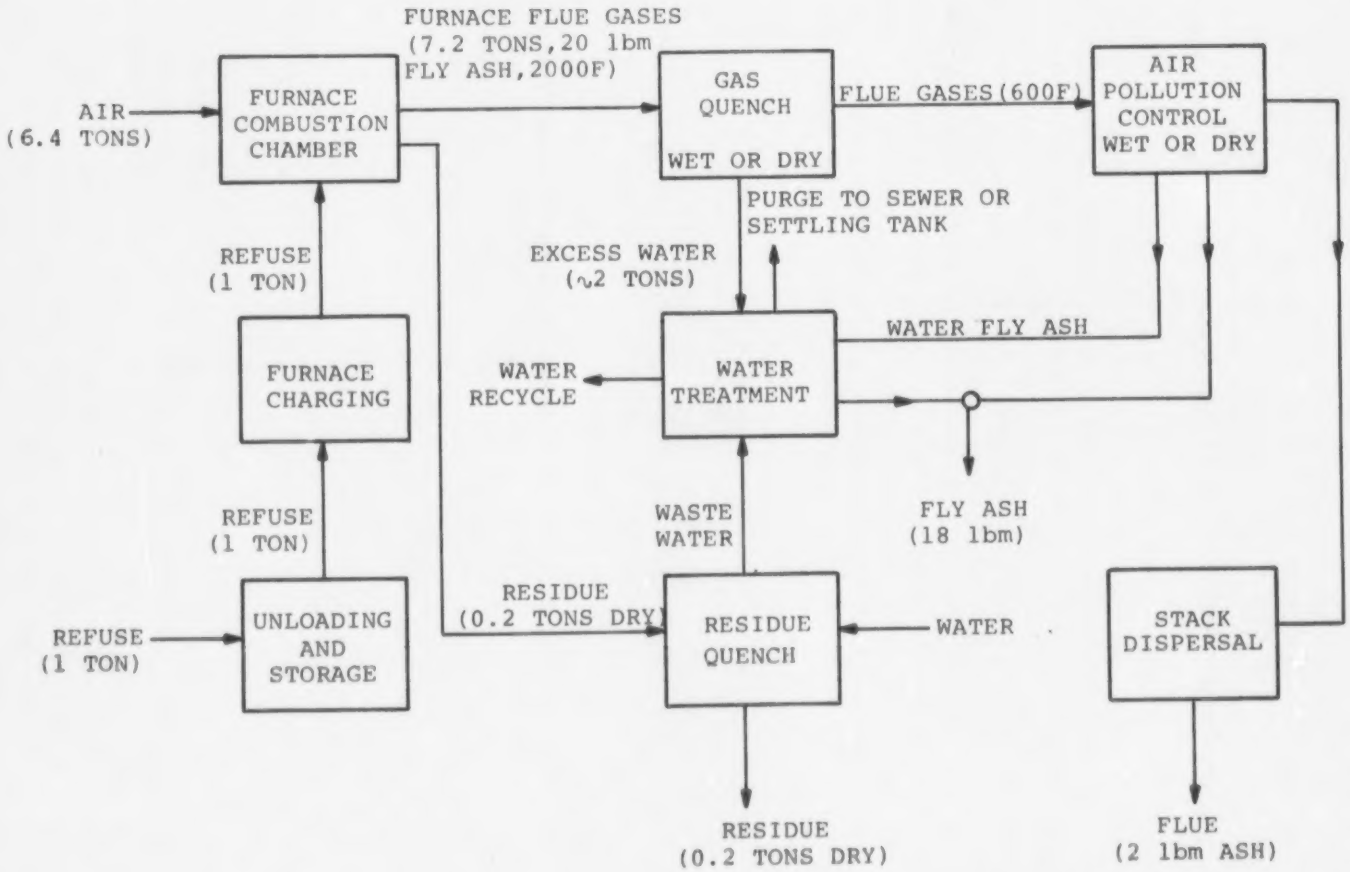

FURNACE FLUE GASES (7.2 TONS,20 lbm FLY ASH,2000F)
AIR (6.4 TONS)
FURNACE COMBUSTION CHAMBER
GAS QUENCH WET OR DRY
FLUE GASES(600F)
AIR POLLUTION CONTROL WET OR DRY
REFUSE (1 TON)
PURGE TO SEWER OR SETTLING TANK
EXCESS WATER (~2 TONS)
WATER FLY ASH
FURNACE CHARGING
WATER RECYCLE
WATER TREATMENT
REFUSE (1 TON)
WASTE WATER
FLY ASH (18 lbm)
RESIDUE (0.2 TONS DRY)
REFUSE (1 TON)
UNLOADING AND STORAGE
RESIDUE QUENCH
WATER
STACK DISPERSAL
RESIDUE (0.2 TONS DRY)
FLUE (2 lbm ASH)

Figure 26. Basic components of an incinerator. (Note: Quantities in parentheses are rough measures of flow rates and temperatures.) english units

The storage pit or bunker normally provides several days storage capacity for the facility. The grab deposits the refuse into the furnace feed or charging chute, and then the refuse is normally gravity fed into the furnace. The charging hoppers are usually water cooled and are always kept filled to capacity in order to prevent hot gases from entering the refuse storage area. Most incinerators are operated under negative pressure to prevent the escape of hot gases and odors from the system.

A variety of furnace designs have been developed for burning refuse. Most of the units are designed for mass burning the raw refuse, and no special processing is required. The refuse is conveyed through the furnace by some type of stoker system, e.g., traveling-grate, chain grate, reciprocating stoker, stepped grate, shaking stoker, rocker grate, rotating grate stoker (rotating barrels) and rotary drum (rotary kiln). The refuse is dried and burned on the stoker unit, with air being introduced from both under the stoker and over the refuse. In water wall units a minimum of excess air is required. The residue from combustion is normally carried by the stoker to a water quencher. The quench pit can serve as a water seal to the furnace.

The stoker unit is not only required to convey the refuse through the furnace but also to agitate the refuse, permitting more complete combustion. Several furnace designs include auxiliary burners to assist in combustion of the refuse. This may be required in cases where wet refuse is frequently encountered.

The residue from refuse incineration is usually a wet complex mixture of metal, glass, slag, charred and unburned organics and ash. In some incinerator units the residue is collected dry. This residue (wet or dry) is usually disposed of in a landfill. In some units the residue is passed through a rotary screen which separates the metal from the ash; the metal is recovered, and the ash is used as a road bed fill. The United States Bureau of Mines and the Raytheon Company have developed a process (23) which recoveres metal, and glass from the incinerator residue. However, this system has not been commercially proven.

The hot gases leaving the furnace chamber contain the products of combustion, particulates, and other gases released by thermal decomposition of the raw refuse. These hot gases can be passed through a boiler unit before being treated in a gas cleaning unit. Air pollution codes require the removal of particulates from the gas before they can be released to the atmosphere. Although a number of different types of particulate removal systems are availabe, electrostatic precipitators are reported to be the most effective. Reports to date indicate that the precipitator units achieve 95 to 99%

efficiency, and meet the required EPA performance levels. The fly ash collected is usually added to the incinerator residue for disposal.

In an electrostatic precipitator, solid particles in the flue gas are electrostatically charged by a high-voltage discharge and the gas is passed through a high voltage electrostatic field where the solid particles are attracted to a negatively charged collection surface. The collected particles are either shaken or hosed down from the collecting surface periodically. Optimum operating temperatures for the precipitators are between 232 and 288°C (450 and 550°F). Since the flue gases from the incinerator can average from 649 to 760°C (1200 to 1400°F) it is necessary to cool the gases before gas cleaning. For the flow plan proposed the hot gases will be cooled by passing them through a rotary dryer unit.

Reactor/Heat Exchanger/Scrubber and Caustic Tank

The dried lights at an approximate temperature of 149°C (300°F) will be transported a short distance to a rotary reactor for embrittlement treatment with heated HCl. The HCl gas will be heated to 149°C (300°F) in the heat exchanger by a portion of the hot incinerator flue gases. To minimize corrosion problems and to facilitate the embrittlement process, it is desirable to maintain a processing temperature of 149°C (300°F). It is anticipated that the light fraction will be retained in the reactor for about five minutes. The treated refuse will then be conveyed to a ball mill and the process gas recycled for reuse. It is estimated that no more than 2% of the HCl would be retained with the treated waste. For the proposed embrittlement treatment a reactant gas mixture of 50% HCl/50% air by volume is assumed. However, to minimize the potential for fire or explosion it may be necessary to consider the use of an oxygen deficient gas (flue gas from the precipitator) as the carrier medium for the HCl. The recycled gas plus the make-up gas would be heated in a heat exchanger using hot flue gases from the incinerator. A conventional heat exchanger of the shell and tube type could be used for this application. As backup, if the HCl cannot be recycled, a scrubber unit with caustic solution is proposed.

Ball Mill and Rotary Disc Screen

The embrittled light fraction would be transported a short distance to a ball mill for fine grinding and then to a rotary disc screen to remove the oversized fraction. Ball mills are horizontal cylinders with a diameter about equal to their length. The mills are about half-filled with quartz pebbles or iron balls. The horizontal rotation of the mill causes the balls and the charge to cascade from the side wall back to the center of the mill. The action of the balls rolling over each other cause the friable charge to be ground into a powder. A continuous feed process can be used with the retention time controlled by the feed rate. A rotary disc screen is proposed for screening the discharge from the ball mill because of its effectiveness in classifying shredded waste. The oversized fraction would be conveyed to the incinerator for combustion. The powdered fraction would be conveyed to a storage bin and then transported to the fuel customer.

MATERIAL AND ENERGY BALANCE

Using the flow plan developed, a detailed material balance and energy balance were developed. The data developed were based on a plant processing 907 mt (1000 tons) of raw refuse per day. Also, it was assumed that a landfill was available to serve as a backup to this facility. The landfill would provide disposal capability for waste deliveries in excess of 907 mt/day (1000 tons/day), for residue from the plant, and for those times when the plant or part of the process was down for repairs. It should be recognized that the projected distribution for the refuse components at each stage of the flow is based on that expected for an average refuse system. The fluctuations in refuse due to seasonal changes and the usual daily variations result in moisture and compositional changes that can alter the behavior of the waste products at each stage of the resource recovery process. The material balance presented in Table 23 (metric units) and Table 24 (English units) and shown in Figure 27 (metric units) and Figure 28 (English units) was based on data collected from University of Dayton studies (22), the Bureau of Mines pilot studies (24), the St. Louis Demonstration Plant (25), NCRR reports (26), the Ralph M. Parsons Company report (27), the thesis by J. Ruf (19), and from manufacturers of resource recovery equipment. The starting values used for the different refuse components were taken from the data compiled in the thesis by J. Ruf. The values specified were used as a model for simulating the resource recovery processes defined in the flow plan. The energy balance developed is presented in Figure 29 (metric units) and Figure 30 (English units).

As shown in Figures 29 and 30 the energy efficiency of the proposed facility is 60.1%. This calculation does not include the energy that would be saved by recycling of ferrous metal. A facility replacing virgin iron ore with 60.3 mt (66.5 tons) of ferrous scrap a day would save approximately 2033.6 mKj (1,928 million BTU) Inclusion of the energy conserved by recycling the ferrous scrap would give the resource recovery facility an energy efficiency of 82%.

TABLE 23. MATERIAL BALANCE, METRIC TONS

Process	Paper and paper products	Plastics	Textiles	Wood	Food and garden wastes	Glass	Sand and rock	Ferrous metal	Non-ferrous metal	Total	Destination
Trommel (12.7-cm opn)	453.5	40.9	13.6	54.4	163.3	63.5	40.8	68.0	9.0	907	Entering
+12.7-cm	299.3	20.0	4.5	13.6	45.4	4.5	4.5	18.0	1.8	412	To shredder
-12.7-cm	154.2	20.9	9.1	40.8	118	59.0	36.3	50	7.2	495	To magnet[1]
Shredder	299.3	20.0	4.5	13.6	45.4	4.5	4.5	18.0	1.8	412	To magnet[2]
Magnet[1]	154.2	20.9	9.0	40.8	117.9	59.0	36.3	49.9	7.2	495	Entering
Ferrous	1.8	0.9	0.9	--	3.6	--	--	41	2.0	50	To cleaning magnet
Nonferrous	152.4	20.0	8.1	40.8	114.4	59.0	36.3	9	5.2	445	To 1/2" trommel
Magnet[2]	299.3	20.0	4.5	14	45.4	4.5	4.5	18.1	1.8	411.8	Entering
Ferrous	3.6	0.9	.9	--	1.8	--	--	15.4	.4	23	To cleaning magnet
Nonferrous	295.7	19.1	3.6	14	43.6	4.5	4.5	2.7	1.4	388.8	To air classifier
Cleaning magnet	5.4	1.8	1.8	--	5.4	--	--	56.0	2.3	72.7	Entering
Ferrous	0.9	--	--	--	1.8	--	--	56.0	1.4	60.1	To ferrous compactor then ferrous bin
Nonferrous	4.5	1.8	1.8	--	3.6	--	--	--	0.9	12.6	To air classifier
Trommel (1.3-cm opn)	152.4	20.0	8.2	41	114.1	59	36.3	9.0	5.4	445	Entering
+1.3-cm	152.4	19.8	8.1	39.2	62.5	58.5	11.8	8.9	5.2	366	To air classifier
-1.3-cm	--	0.2	.1	1.8	51.6	.5	24.5	.1	.2	79	To incinerator
Air classifier	452.6	40.6	13.5	52.6	109.7	63.1	16.3	11.5	7.5	767.4	Entering
Heavies	35.0	3.9	2.2	25.4	22.7	62.6	11.3	9.2	6	178.3	To incinerator
Lights	417.6	36.7	11.3	27.2	87	.5	5	2.3	1.5	589.1	To dryer
Dryer	417.6	36.7	11.3	27.2	87.1	0.5	5	2.2	1.5	589.1	Entering
Moisture	59	4.5	1.8	3.6	45.4	--	.9	.5	1.5	115.7	Exhausted
Solids	358.6	32.2	9.5	23.6	41.7	0.5	4.1	1.7	1.5	473.4	To reactor
Reactor	358.6	32.2	9.5	23.6	41.7	0.5	4.1	1.7	1.5	473.4	Entering
Hcl pick-up	366	32.6	10.7	25.2	42.6	0.5	4.1	1.7	1.5	484.9	To ball mill
Ball mill	366	32.6	10.7	25.2	42.6	0.5	4.1	1.7	1.5	484.9	To rotary screen

TABLE 23. MATERIAL BALANCE, METRIC TONS (Concluded)

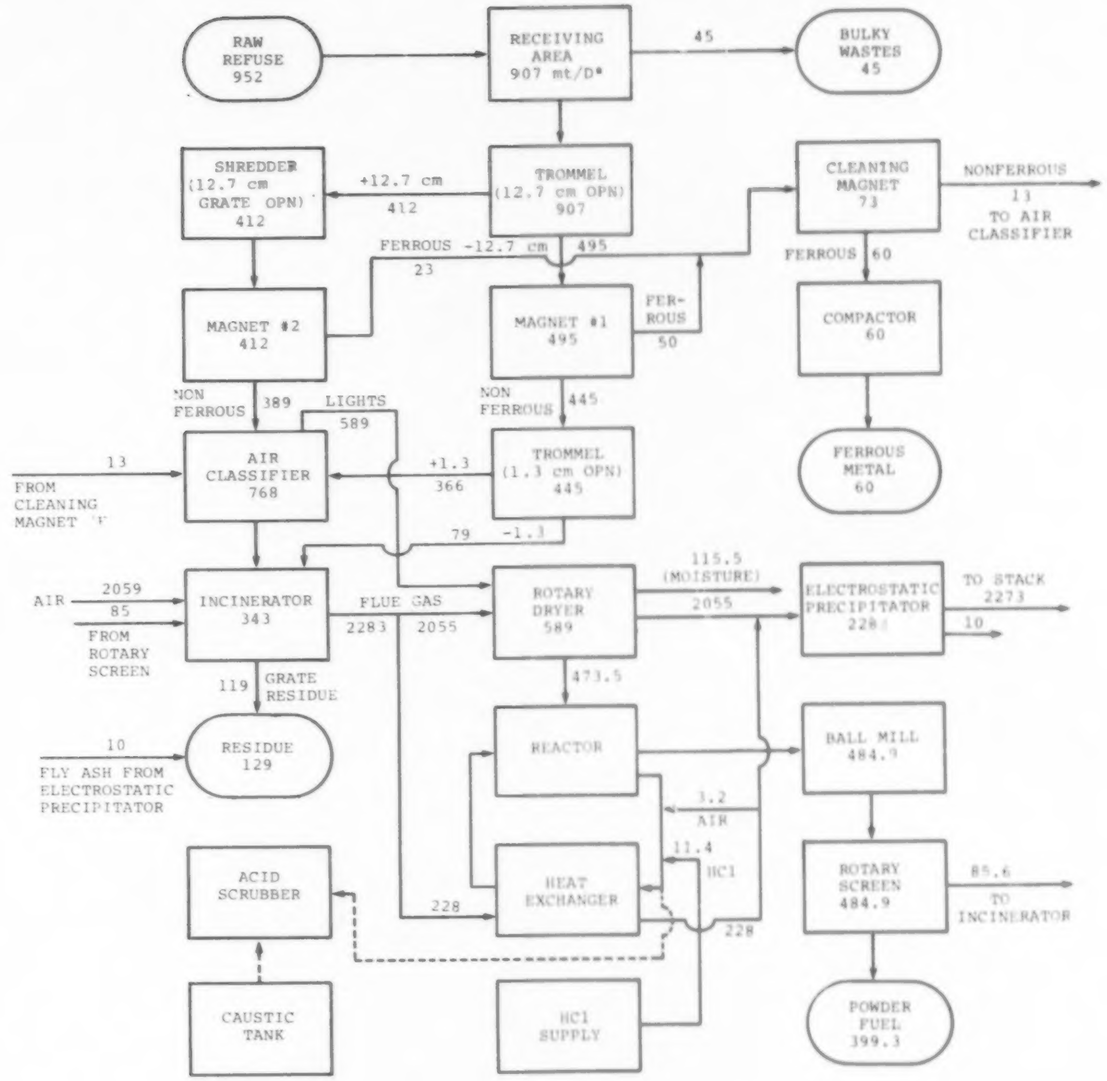
Process	Paper and paper products	Plastics	Textiles	Wood	Food and garden wastes	Glass	Sand and rock	Ferrous metal	Non-ferrous metal	Total	Destination
Rotary screen	366	32.6	10.7	25.2	42.6	0.5	4.1	1.7	1.5	484.9	Entering
+0.3-cm	36.6	16.3	2.17	6.3	19.9	0.23	2.3	1.9	1.9	85.6	To incinerator
-0.3-cm	329.4	16.3	8.53	18.9	22.7	0.23	1.8	0.8	.6	399.3	To fuel storage
Incinerator	71.6	20.5	4.4	33.5	94.3	63.3	38.1	10.4	7.1	342.9	Entering
Moisture	7.3	1.4	0.9	4.5	47.2	1.8	0.9	0.2	0.2	64.4	
Ash	2.4	2.0	.1	.9	1.2	61.5	37.2	10.2	6.9	122.3	
Organics	61.9	17.0	3.9	28.1	46	--	--	--	--	156.4	
Fly ash	1.2	--	0.2	0.9	0.9	3.6	2.1	0.5	0.5	10.5	
Bottom ash	3.3	2.1	0.5	1.3	3	57.9	34.5	9.8	6.4	118.8	
Combustible organics and HCl (2.2)	59.8	17.0	2.7	26.8	43.2	--	--	--	--	149.5	
K Joules x 10^6	1075.9	453.6	61.2	501.0	622.3	12.7	7.4	17.9	11.6	2763.6	

TABLE 24. MATERIAL BALANCE, ENGLISH EQUIVALENTS

Process	Paper and paper products	Plastics	Textiles	Wood	Food and garden wastes	Glass	Sand and rock	Ferrous metal	Non-ferrous metal	Total	Destination	Process notes
Trommel (5-in opn)	500	45	15	60	180	70	45	75	10	1000	Entering	(4,500 BTU/lb)
+5-in	330	22	5	15	50	5	5	20	2	454	To shredder	
-5-in	170	23	10	45	130	65	40	55	8	546	To magnet^1	
Shredder	330	22	5	15	50	5	5	20	2	454	To magnet^2	
Magnet^1	170	23	10	45	130	65	40	55	8	546	Entering	
Ferrous	2	1	1	--	4	--	--	45	2	55	To cleaning magnet	
Nonferrous	168	22	9	45	126	65	40	10	6	491	To 1/2" trommel	
Magnet^2	330	22	5	15	50	5	5	20	2	454	Entering	
Ferrous	4	1	1	--	2	--	--	17	0.5	22.5	To cleaning magnet	
Nonferrous	326	21	4	15	48	5	5	3	1.5	428.5	To air classifier	
Cleaning magnet	6	2	2	--	6	--	--	62	2.5	80.5	Entering	
Ferrous	1	--	2	--	2	--	--	62	1.5	66.5	To ferrous compactor then to ferrous bin	
Nonferrous	5	2	--	--	4	--	--	--	1	14	To air classifier	
Trommel (1/2-in opn)	168	22	9	45	126	65	40	10	6	491	Entering	
+1/2-in	168	21.8	8.9	43	69	64.5	13	9.9	5.8	403.9	To air classifier	
-1/2-in	--	0.2	0.1	2	57	0.5	27	0.1	0.2	87.1	To incinerator	
Air classifier	499	44.8	14.9	58	121	69.5	18	12.9	8.3	846.4	Entering	
Heavies	38.6	4.3	2.4	28	25	69.0	12.5	10.5	6.6	196.9	To incinerator	
Lights	460.4	40.5	12.5	30	96	0.5	5.5	2.4	1.7	649.5	To dryer	

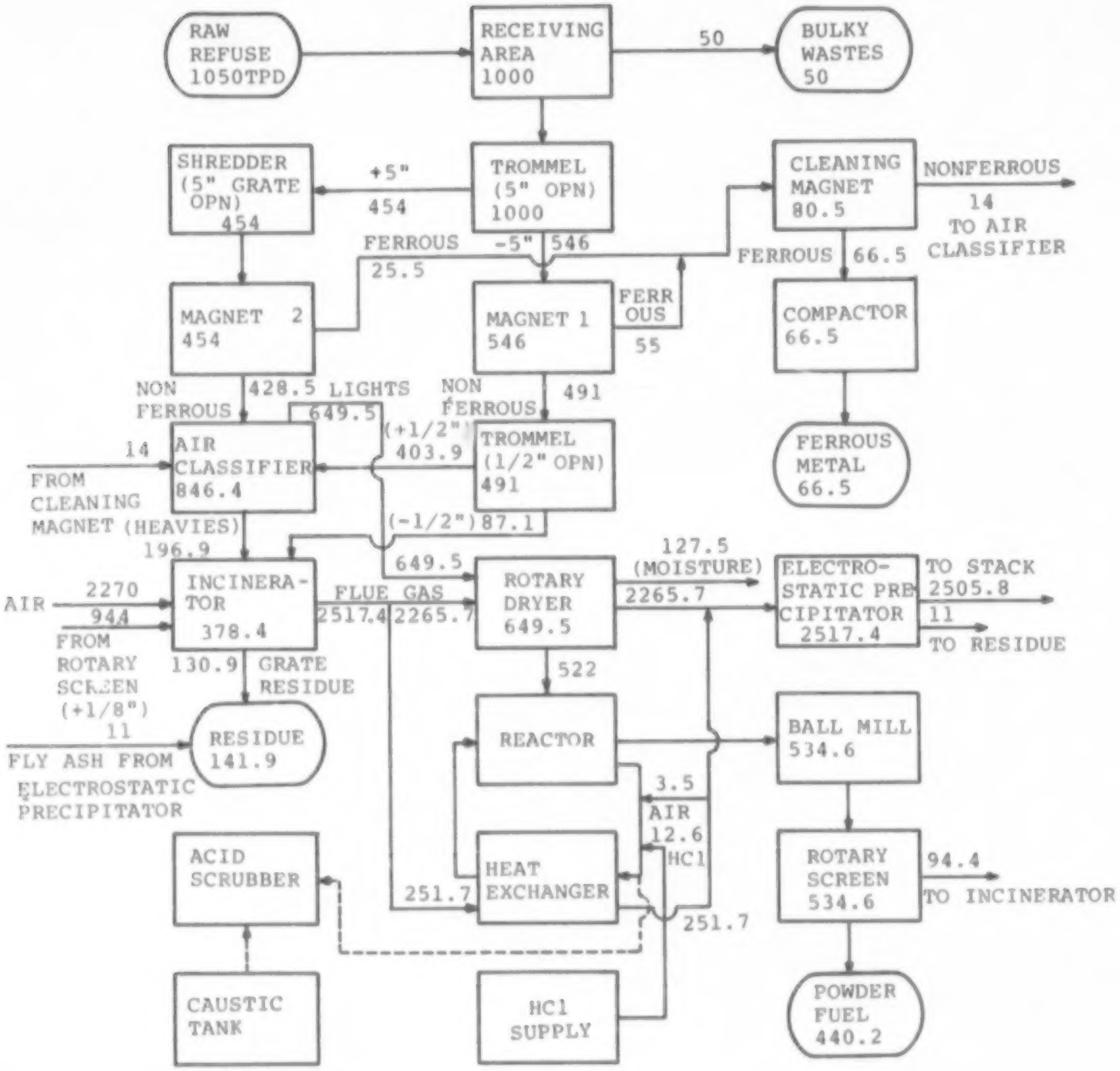
TABLE 24. MATERIAL BALANCE, ENGLISH EQUIVALENTS (Concluded)

Process	Paper and paper products	Plastics	Textiles	Wood	Food and garden wastes	Glass	Sand and rock	Ferrous metal	Non-ferrous metal	Total	Destination	Process notes
Dryer	460.4	40.5	12.5	30	96	0.5	5.5	2.4	1.7	649.5	Entering	Ash-6%; total moisture-24%; moisture evaporated-19.6%; heat for drying-367.7x10^6-BTU;
Moisture	65	5	2	4	50	--	1.0	0.5	--	127.5	Exhausted	
Solids	395.4	35.5	10.5	26	46	0.5	4.5	1.9	1.7	522	To reactor	
Reactor	395.4	35.5	10.5	26	46	0.5	4.5	1.9	1.7	522	Entering	
HCl pick-up	403.5	36	11.75	27.8	47	0.5	4.5	1.9	1.7	534.6	To ball mill	(HCl gain 12.6)
Ball mill	403.5	36	11.75	27.8	47	0.5	4.5	1.9	1.7	534.6	To rotary screen	
Rotary screen	403.5	36	11.75	27.8	47	0.5	4.5	1.9	1.7	534.6	Entering	
+1/8-in	40.3	18	2.35	7.0	22	0.25	2.5	1	1	94.4	To incinerator	
-1/8-in	363.2	18	9.40	20.8	25	0.25	2.0	0.9	0.7	440.25	To fuel storage	(-6,516 x 10^6 BTU's)
Incinerator	78.9	22.5	4.8	37.0	104	69.8	42	11.6	7.8	378.4	Entering	Air required at 100% excess=378.35 x 2 x 3= 2270 tons
Moisture	8	1.5	1	5	52	2	1	0.3	0.2	71		(18.8%)
Ash	2.6	2.3	0.1	1	1.3	67.8	41	11.3	7.6	135		(35.6%)
Organics	68.3	18.7	3.7	31.0	50.7	--	--	--	--	172.4		(45.6%)
Fly ash	1.3	--	0.1	1.0	1.0	4	3	0.5	0.5	11.6		(3%) to electrostatic precipitator (95% trapped)
Bottom ash	3.6	2.3	0.6	1.5	3.3	63.8	38	10.8	7.1	131.0		(34.6%) to landfill with 95% fly ash-141.95
Combustibles, organics & HCl (2.2)	66	18.7	2.95	29.5	47.7	--	--	--	--	164.8		(43.6%) total gas 2521 ton per day
BTU's x 10^6	1020	430	58	475	590	12	7	17	11	2620		(3460 BTU/%) about 60% available for drying at 1560 x 10^6 BTU


RAW REFUSE 952
RECEIVING AREA 907 mt/D*
45
BULKY WASTES 45
SHREDDER (12.7 cm GRATE OPN) 412
+12.7 cm
412
TROMMEL (12.7 cm OPN) 907
CLEANING MAGNET 73
NONFERROUS
13
TO AIR CLASSIFIER
FERROUS -12.7 cm
23
495
FERROUS 60
MAGNET #2 412
MAGNET #1 495
FER-ROUS
50
COMPACTOR 60
NON FERROUS
389
LIGHTS
589
NON FERROUS
445
13
FROM CLEANING MAGNET
AIR CLASSIFIER 768
+1.3
366
TROMMEL (1.3 cm OPN) 445
FERROUS METAL 60
79
-1.3
115.5 (MOISTURE)
AIR
2059
85
FROM ROTARY SCREEN
INCINERATOR 343
FLUE GAS
2283
2055
ROTARY DRYER 589
2055
ELECTROSTATIC PRECIPITATOR 2283
TO STACK 2273
10
119
GRATE RESIDUE
473.5
10
FLY ASH FROM ELECTROSTATIC PRECIPITATOR
RESIDUE 129
REACTOR
BALL MILL 484.9
3.2
AIR
11.4
HCl
ACID SCRUBBER
HEAT EXCHANGER
228
228
ROTARY SCREEN 484.9
85.6
TO INCINERATOR
CAUSTIC TANK
HCl SUPPLY
POWDER FUEL 399.3

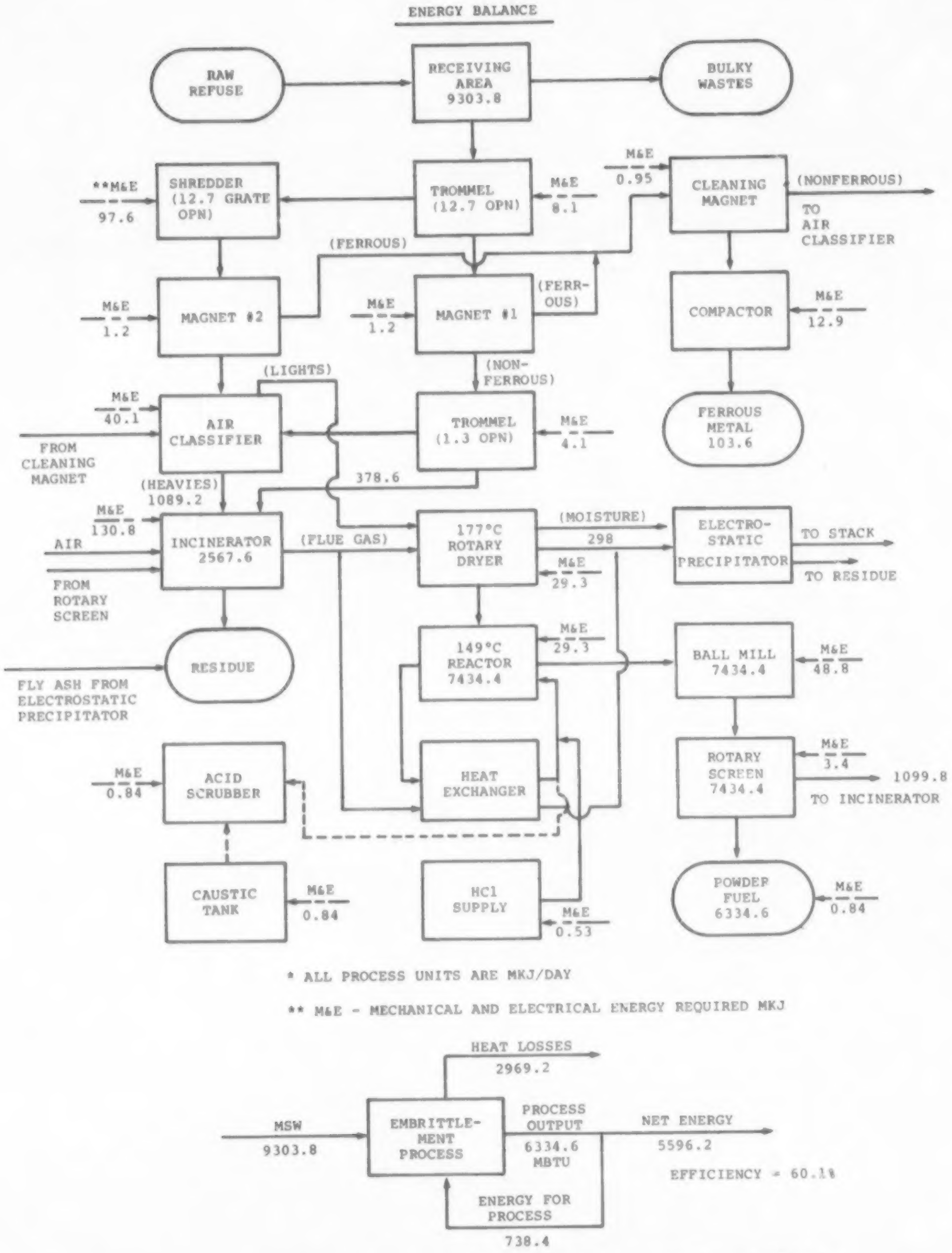
* ALL PROCESS UNITS ARE METRIC TONS/DAY

Figure 27. Material balance flow plan (metric units).


RAW REFUSE 1050TPD
RECEIVING AREA 1000
50
BULKY WASTES 50
SHREDDER (5" GRATE OPN) 454
+5"
454
TROMMEL (5" OPN) 1000
CLEANING MAGNET 80.5
NONFERROUS
14
TO AIR CLASSIFIER
FERROUS
25.5
-5" 546
FERROUS 66.5
MAGNET 2 454
MAGNET 1 546
FERR OUS
55
COMPACTOR 66.5
NON FERROUS
428.5
LIGHTS
649.5
NON FERROUS
491
(+1/2")
403.9
14
AIR CLASSIFIER 846.4
FROM CLEANING MAGNET (HEAVIES)
TROMMEL (1/2" OPN) 491
FERROUS METAL 66.5
(-1/2") 87.1
196.9
649.5
127.5 (MOISTURE)
AIR
2270
944
FROM ROTARY SCREEN (+1/8")
INCINERATOR 378.4
FLUE GAS
2517.4
2265.7
ROTARY DRYER 649.5
2265.7
ELECTROSTATIC PRECIPITATOR 2517.4
TO STACK 2505.8
11
TO RESIDUE
130.9
GRATE RESIDUE
522
11
FLY ASH FROM ELECTROSTATIC PRECIPITATOR
RESIDUE 141.9
REACTOR
BALL MILL 534.6
3.5
AIR
12.6
HCl
ACID SCRUBBER
251.7
HEAT EXCHANGER
251.7
ROTARY SCREEN 534.6
94.4
TO INCINERATOR
CAUSTIC TANK
HCl SUPPLY
POWDER FUEL 440.2

*ALL PROCESS UNITS ARE TONS/DAY

Figure 28. Material balance flow plan (English equivalents).

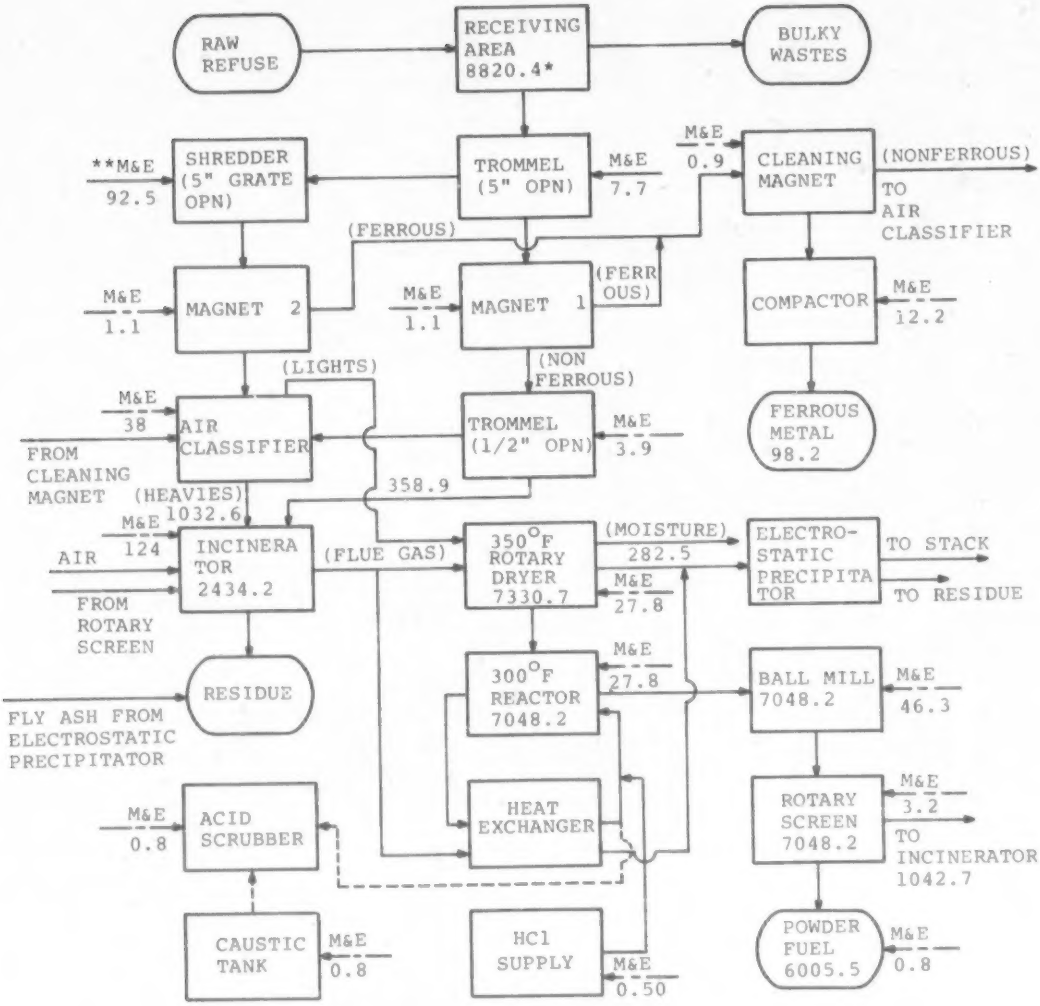

ENERGY BALANCE
RAW REFUSE
RECEIVING AREA 9303.8
BULKY WASTES
**M&E 97.6
SHREDDER (12.7 GRATE OPN)
TROMMEL (12.7 OPN)
M&E 8.1
M&E 0.95
CLEANING MAGNET
(NONFERROUS)
TO AIR CLASSIFIER
(FERROUS)
M&E 1.2
MAGNET #2
M&E 1.2
MAGNET #1
(FERROUS)
COMPACTOR
M&E 12.9
(LIGHTS)
(NON-FERROUS)
M&E 40.1
AIR CLASSIFIER
TROMMEL (1.3 OPN)
M&E 4.1
FERROUS METAL 103.6
FROM CLEANING MAGNET
(HEAVIES) 1089.2
378.6
M&E 130.8
AIR
INCINERATOR 2567.6
(FLUE GAS)
177°C ROTARY DRYER
(MOISTURE) 298
ELECTRO-STATIC PRECIPITATOR
TO STACK
TO RESIDUE
FROM ROTARY SCREEN
M&E 29.3
M&E 29.3
149°C REACTOR 7434.4
BALL MILL 7434.4
M&E 48.8
FLY ASH FROM ELECTROSTATIC PRECIPITATOR
RESIDUE
M&E 0.84
ACID SCRUBBER
HEAT EXCHANGER
ROTARY SCREEN 7434.4
M&E 3.4
1099.8 TO INCINERATOR
CAUSTIC TANK
M&E 0.84
HCl SUPPLY
M&E 0.53
POWDER FUEL 6334.6
M&E 0.84
HEAT LOSSES 2969.2
MSW 9303.8
EMBRITTLE-MENT PROCESS
PROCESS OUTPUT 6334.6 MBTU
NET ENERGY 5596.2
EFFICIENCY = 60.1%
ENERGY FOR PROCESS 738.4

* ALL PROCESS UNITS ARE MKJ/DAY

** M&E - MECHANICAL AND ELECTRICAL ENERGY REQUIRED MKJ

Figure 29. Energy balance flow plan (metric units).

ENERGY BALANCE


RAW REFUSE
RECEIVING AREA 8820.4*
BULKY WASTES
**M&E 92.5
SHREDDER (5" GRATE OPN)
TROMMEL (5" OPN)
M&E 7.7
M&E 0.9
CLEANING MAGNET
(NONFERROUS)
TO AIR CLASSIFIER
(FERROUS)
M&E 1.1
MAGNET 2
M&E 1.1
MAGNET 1
(FERROUS)
COMPACTOR
M&E 12.2
(NON FERROUS)
(LIGHTS)
M&E 38
AIR CLASSIFIER
FROM CLEANING MAGNET
TROMMEL (1/2" OPN)
M&E 3.9
FERROUS METAL 98.2
358.9
(HEAVIES) 1032.6
M&E 124
AIR
INCINERATOR 2434.2
FROM ROTARY SCREEN
(FLUE GAS)
350°F ROTARY DRYER 7330.7
(MOISTURE) 282.5
M&E 27.8
ELECTROSTATIC PRECIPITATOR
TO STACK
TO RESIDUE
RESIDUE
FLY ASH FROM ELECTROSTATIC PRECIPITATOR
300°F REACTOR 7048.2
M&E 27.8
BALL MILL 7048.2
M&E 46.3
M&E 0.8
ACID SCRUBBER
HEAT EXCHANGER
ROTARY SCREEN 7048.2
M&E 3.2
TO INCINERATOR 1042.7
CAUSTIC TANK
M&E 0.8
HCl SUPPLY
M&E 0.50
POWDER FUEL 6005.5
M&E 0.8

* ALL PROCESS UNITS ARE MBTU/DAY

** M&E - MECHANICAL AND ELECTRICAL ENERGY REQUIRED MBTU

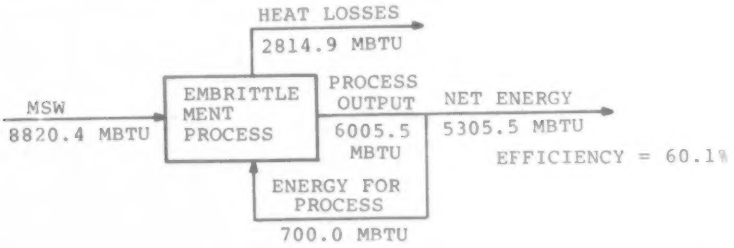

HEAT LOSSES
2814.9 MBTU
MSW
8820.4 MBTU
EMBRITTLEMENT PROCESS
PROCESS OUTPUT
6005.5 MBTU
NET ENERGY
5305.5 MBTU
EFFICIENCY = 60.1%
ENERGY FOR PROCESS
700.0 MBTU

Figure 30. Energy balance flow plan (English equivalents).

PROPOSED PLANT LAYOUT

Utilizing the flow plan developed, the material balance, and available manufacturing data, a layout for a plant to produce powdered fuel from refuse was developed.

Equipment Specifications

The equipment needed for each of the processing steps specified in the flow plan are defined and listed in Table 26. A potential supplier, model number, power requirements for the specific hourly capacity, and cost are listed.

Floor Plan

Utilizing the data compiled in Table 26, a floor plan arrangement was developed. A schematic showing the proposed plant layout is presented in Figure 31. The arrangement shown was selected through a trial and error process with the final arrangement selected being the one most compatible with space available and the special requirements needed for interfacing the different items of equipment. A detailed floor plan for the office and maintenance area is shown in Figure 32. Elevations through different sections of the proposed plant are shown in Figures 33 through 35. The receiving area, 45.7m x 24.4m (150ft x 80ft), was determined by allowing both ample maneuvering area for the front end loaders and a refuse storage area large enough to accommodate one day of refuse. The remaining area of the plant was designed to accommodate the processing equipment. The processing building is to be constructed of concrete and glass panels on an exposed steel structural system. Concrete was chosen for its durability and chemical resisting properties, glass panels to allow natural light into the plant, while steel was used because of the long spans involved.

The maintenance area provides space for repairing the processing equipment, a locker room, restrooms, a lunch room, and foreman offices. The administrative area provides space for payroll, billing, and supervisory personnel needed to allow the plant to be self-sufficient. Also included is a small quality control lab, engineers office, and conference room. The bag houses and after-burner unit for odor control, the exhaust fans, and the cyclone units will be located on the roof of the main processing building. A parking lot adjacent to the main building provides parking for plant and office employees. The buildings and grounds will be enclosed with a chain-link fence. The security for the facility would be by television monitors and security patrol.

The proposed resource recovery plant is designed to process 907 mt (1000 ton) of municipal solid waste per day. The plant would receive refuse 16 hr/day, 7 day/week. The

TABLE 25. EQUIPMENT LIST

	Equipment identification*	Manufacturer	Nominal capacity mt/hr (ton/hr)	Model no.	1978 Equipment Cost+	Total power requirement kw (HP)
1.	2-Trommels (12.7-cm) (5-in opn)	Triple/S Dynamics	22.7 (25 ea)	6 x25	$ 53,500 ea	18.6 (25 ea)
2.	Coarse shredder (12.7-cm) (5-in grate opn)	Gruendler	22.7 (25)	5xE	81,800	447 (600)
3.	Magnetic separator #1	Eriez Magnetic Separation Division	27.2 (30)	48 x48 SR-E	23,525	5.2 (7)
4.	Magnetic separator #2	Eriez Magnetic Separation Division	22.7 (25)	48 x48 SR-E	23,525	5.2 (7)
5.	Cleaning magnet	Eriez Magnetic Separation Division	4.5 (5)	42 x42 SR-P	17,823	4.5 (6)
6.	Trommel (1.3-cm) (1/2-in opn)	Triple/S Dynamics	22.7 (25)	18 x6	41,658	18.6 (25)
7.	2-Air classifiers with cyclones	Radar Systems, Inc.	22.7 (25 ea)	T-79-184ADS	201,500 ea	105 (141)
8.	Metal compactor	Carborundum	13.6 (15)	1000	200,000	373 (500)
9.	2-Rotary dryers	C-E Raymond	31.7 (35)	150 x65 Style M	350,000	67 (90)
10.	2-Rotary reactors	C-E Raymond	27.2 (30)	150 x65 Style M	350,000	67 (90)
11.	2-Ball mill	Koppers Co., Inc.	27.2 (30)	8 x72	65,000	112 (150)
12.	2-Rotary disc screen	Radar System	12.7 (14)	8 Dia.	20,000	
13.	Incinerator (includes the grate unit, wet scrubber, electrostatic precipitator, pit and crane	Contractor Constructed	18.1 (20)	---	5,000,000	600.3 (805 ea)
14.	Heat exchanger	---	---	---	---	---
15.	Bank of HCl tanks	Vendor rented	0.9 (1)	---	---	---

TABLE 25. EQUIPMENT LIST (Concluded)

Equipment identification*	Manufacturer	Nominal capacity mt/hr (ton/hr)	Model no.	1978 Equipment Cost	Total power requirement kw (HP)
16. Acid scrubber	Corning glass	0.009 (.01)	2 x8	$ 10,000	3.7 (5)
17. Caustic tank	Chemtronic System	1887-1 (500 gal)	---	6,376	3.7 (5)
18. Powder storage bin	Butler Manufacturing Company	453.5 (500)	29 x64	67,500	3.7 (5)
19. Conveyors					
a. 2-Apron conveyors	Cindaco	40.8 (45)	12 x20	107,100	15 (20ea)
b. 2-Apron conveyors	Cindaco	40.8 (45)	6 x36	120,500	30 (40ea)
c. 2-Belt conveyors	Cindaco	40.8 (45)	6 x40	26,800	11.2 (15ea)
d. 4-Belt conveyors	Cindaco	40.8 (45)	6 x20	53,600	11.2 (15ea)
e. 3-Belt conveyors	Cindaco	40.8 (45)	6 x15	49,600	11.2 (15ea)
f. 2-Belt conveyors	Cindaco	40.8 (45)	6 x150	40,150	15 (20ea)
g. 2-Belt conveyors	Cindaco	36.3 (40)	4 x20	26,800	11.2 (15ea)
h. 3-Belt conveyors	Cindaco	40.8 (45)	6 x50	40,200	22.4 (30ea)
i. 1-Belt conveyor	Cindaco	18.1 (20)	3 x252	30,000	7.5 (10)
j. 1-Belt conveyor	Cindaco	18.1 (20)	3 x130	30,000	7.5 (10)
k. 2-Belt conveyors	Cindaco	18.1 (20)	3 x50	30,000	7.5 (10ea)
l. 1-Belt conveyor	Cindaco	18.1 (20)	3 x15	12,000	3.7 (5)
m. 1-Belt conveyor	Cindaco	4.5 (5)	2 x15	5,000	3.7 (5)
n. 1-Belt conveyor	Cindaco	13.6 (15)	2 x50	16,600	3.7 (5)

* This list also does not include the following items: (a) plant collecting system; (b) waste water treatment system; (c) traveling bridgecrane; (d) house air supply system; (e) truck scales; (f) heating, ventilating, and air conditioning system; (g) fire protection system; (h) electric power distribution system; (i) front-end loaders; (j) remote control system; and (k) furniture, fixtures, and laboratory equipment.

+ Equipment cost does not include installation cost or contractor cost.

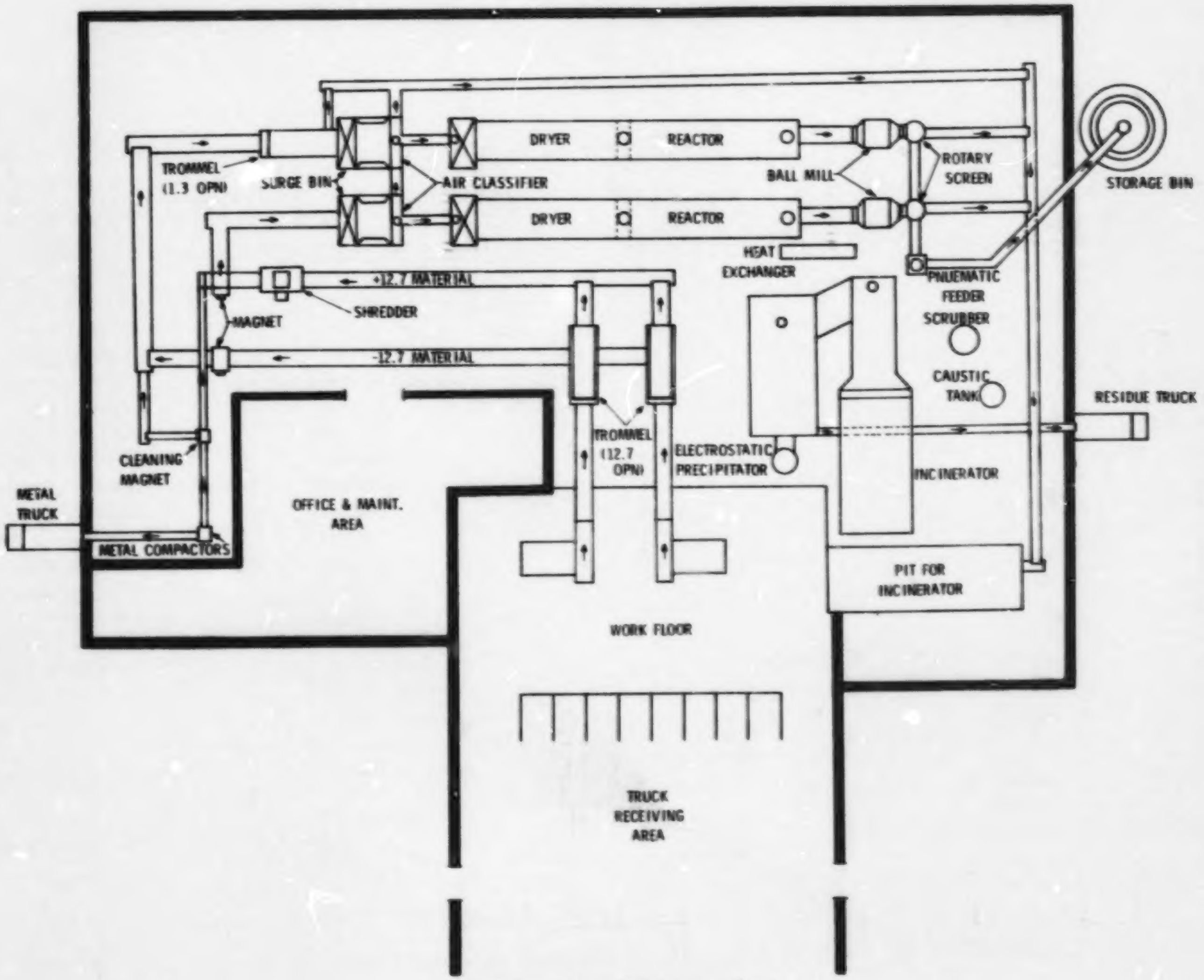

TROMMEL (1.3 OPN)
SURGE BIN
AIR CLASSIFIER
DRYER
REACTOR
DRYER
REACTOR
BALL MILL
ROTARY SCREEN
STORAGE BIN
HEAT EXCHANGER
PNUEMATIC FEEDER
SCRUBBER
CAUSTIC TANK
RESIDUE TRUCK
+12.7 MATERIAL
SHREDDER
MAGNET
-12.7 MATERIAL
TROMMEL (12.7 OPN)
ELECTROSTATIC PRECIPITATOR
INCINERATOR
CLEANING MAGNET
METAL TRUCK
METAL COMPACTORS
OFFICE & MAINT. AREA
PIT FOR INCINERATOR
WORK FLOOR
TRUCK RECEIVING AREA

Figure 31. Floor plan.

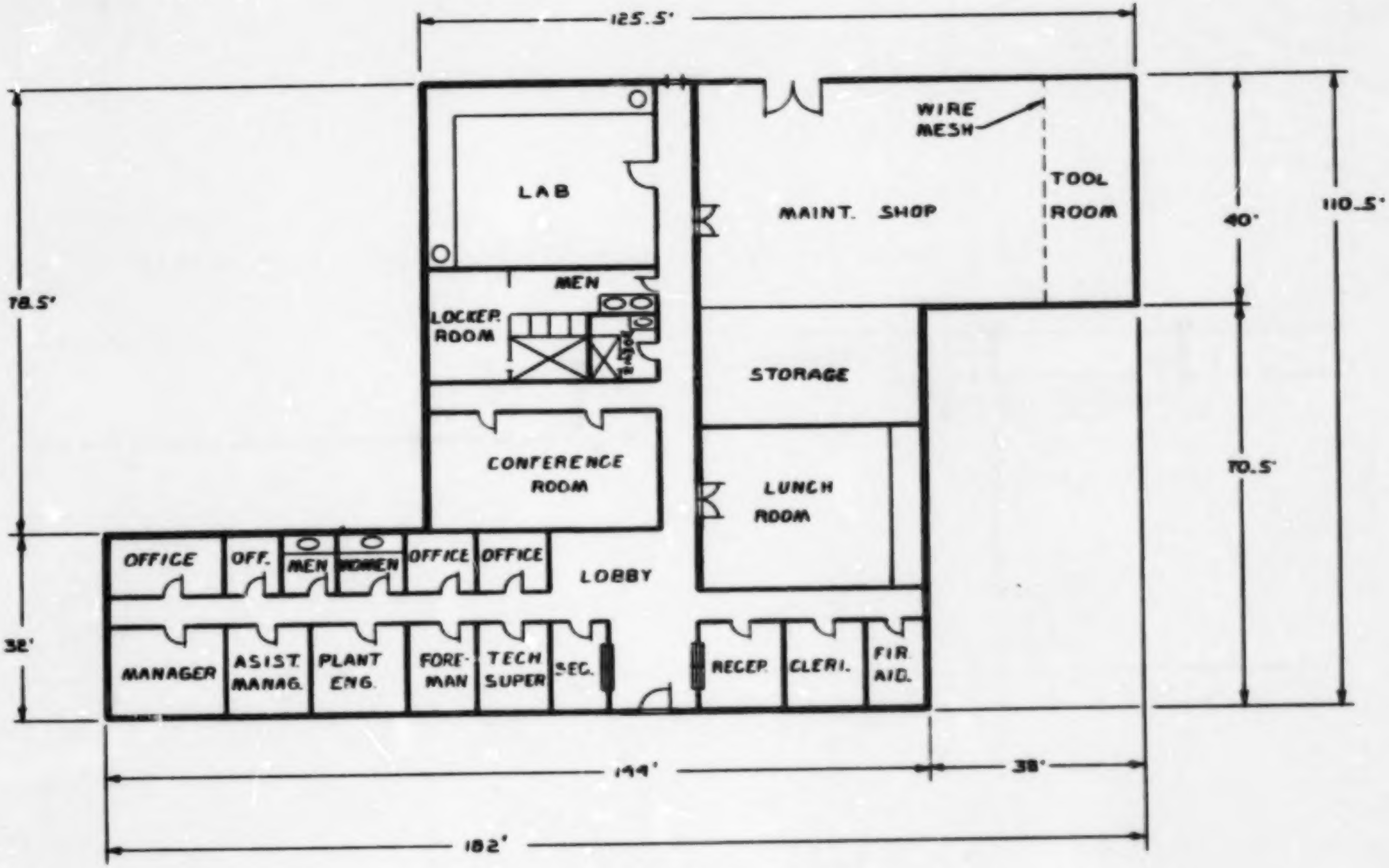

125.5'
78.5'
32'
LAB
MEN
LOCKER ROOM
CONFERENCE ROOM
MAINT. SHOP
WIRE MESH
TOOL ROOM
STORAGE
LUNCH ROOM
LOBBY
OFFICE
OFF.
MEN
WOMEN
OFFICE
OFFICE
MANAGER
ASIST. MANAG.
PLANT ENG.
FORE-MAN
TECH SUPER
SEC.
RECEP.
CLERI.
FIR. AID.
40'
70.5'
110.5'
144'
38'
182'

Figure 32. Office & Maintenance Areas

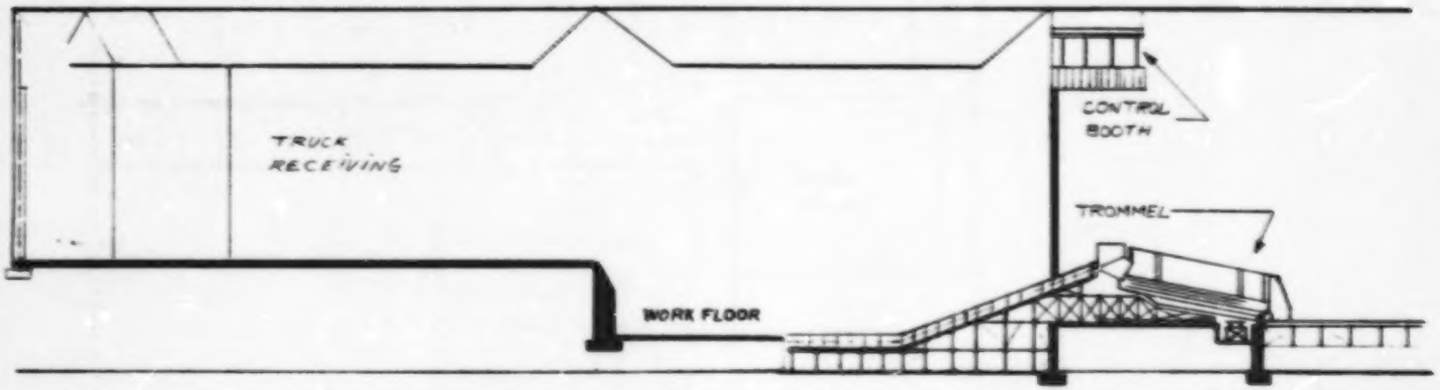

TRUCK RECEIVING
CONTROL BOOTH
TROMMEL
WORK FLOOR

Figure 33. Refuse receiving area and initial trommelling.

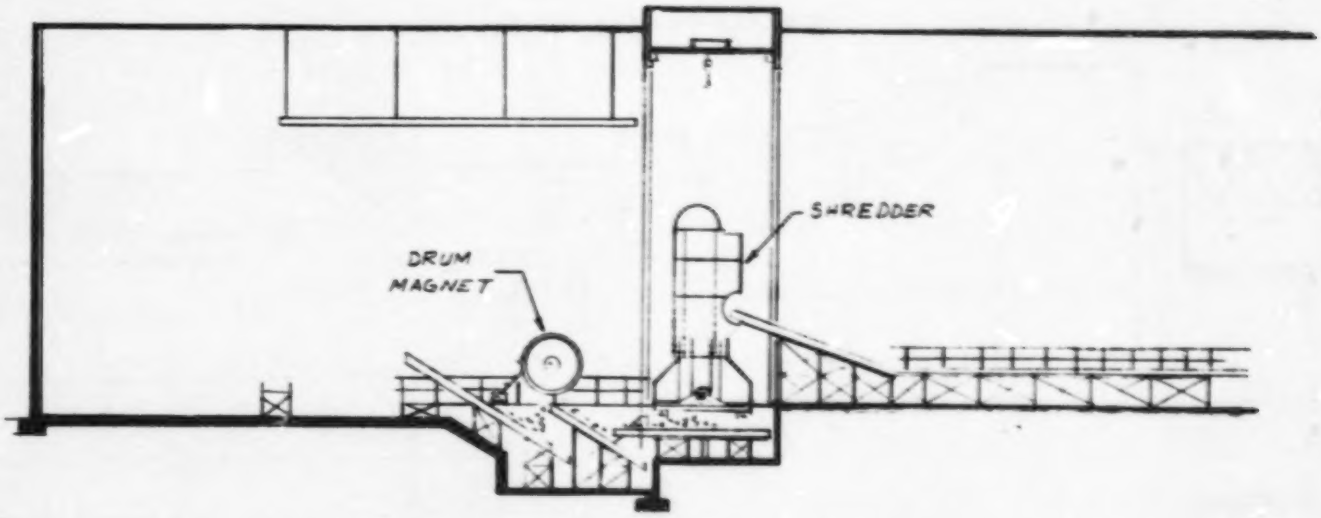

DRUM
MAGNET
SHREDDER

Figure 34. Magnetic recovery and shredding area.

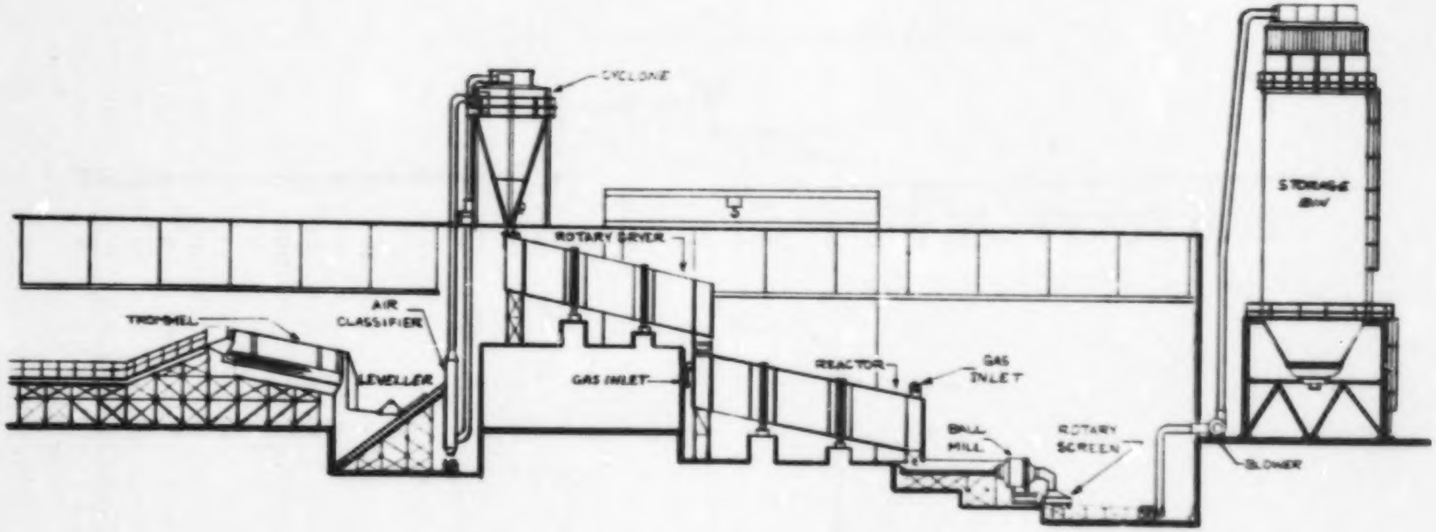

CYCLONE
STORAGE BIN
ROTARY DRYER
TROMMEL
AIR CLASSIFIER
LEVELLER
GAS INLET
REACTOR
GAS INLET
BALL MILL
ROTARY SCREEN
BLOWER

Figure 35. Fuel recovery area.

processing facilities would operate 20 hr/day and the incineration facility would be operated on a 24 hr/day basis. Assuming an on-line availability of 85%, some 281,410 mt (310,250 ton) can be processed annually. It is assumed that the plant will be located in close proximity to a sanitary landfill which will receive the residue from the resource recovery plant and serve as a backup to the plant during periods of shutdown or overage.

Refuse trucks enter the plant and go first to a weigh station and then to the refuse dumping area. The weigh station is used to control traffic into the plant, weigh the incoming refuse and provide a printed record for both the driver and the data processing system. An automatic gate control system is used to regulate the truck flow and prevent vehicles from entering the plant without weighing in. An automatic/manual recording system records the time, date, and gross weight of the truck on the scale, along with the truck tare weight and identification from the plastic data card provided by the driver. Additional data such as billing code, truck route number, etc. can also be recorded. The information collected is retained for billing and a receipt copy is given to the driver. After the cycle is completed, the driver proceeds to the designated tipping stall while a new truck weighs in. For trucks or private vehicles without plastic data cards, a manual recording system is used. Trucks transporting the powdered fuel and ferrous recovered from the refuse will exit through the weigh station so that a record can also be maintained of production.

The flow-through or dumping turnaround time will usually vary from 5 to 10 min and will average about 8 min. Turnaround time extends from the time the truck enters the weigh station to the time it leaves the refuse dumping area. For the proposed plant eight truck unloading stalls are proposed providing the facility with a capability to handle 60 trucks/hr. With this arrangement over 907 mt (1000 ton) of refuse could be handled during the 4 hr peak receiving period if necessary.

The refuse trucks will dump the refuse onto a lower level work floor, 3.7 m (12 ft) below the truck unloading floor. Front end loaders would be used to move the refuse to a storage area or out to a conveyor for processing.

A control tower, 4.6m x 9.8m (15ft x 32ft), is located above the work floor at the beginning of the process lines. The tower houses the electrical controls for all the processing equipment and the traffic control system. An operator stationed in the tower will operate the processing equipment and manage the traffic pattern of vehicles entering the truck receiving area. In addition, from this vantage point the tower operator will provide visual inspection of refuse on the processing lines and coordinate the activities of the front end loader operators.

Two processing lines are proposed for the resource recovery facility. Each processing line would handle 22.7 mt/hr (25 ton/hr). Two front end loaders will deposit the refuse onto two apron conveyors. These 3.7 m (12 ft) wide units would have a belt speed of 1.5 to 4.6 m/min (5 to 15 ft/min). The refuse loaded onto these units would be conveyed onto two 1.8 m (6 ft) wide apron type conveyors having a belt speed of 10.7 m/min (35 ft/min). The assumed density of the refuse feed onto the conveyors is approximately 128.2 kg/m^3 (8 lb/ft^3). The refuse would be transported up a 20° incline to the first processing step -- trommeling. Starting at the incline all conveyors will be enclosed with dust covers to minimize plant housekeeping and dust problems. Refuse inspection would occur on the receiving floor by the operators of the front end loader and on the first stages of the entrance conveyors. Waste unsuitable for processing (tires, tree stumps, white goods, etc.) would be removed at that time.

Two trommels, 1.8m x 7.6m (6ft x 25ft), with 12.7 cm (5 in) circular openings are the first processing stage for the refuse. The oversized waste (+12.7 cm) (+5 in) is conveyed to a hammermill and the undersized (-12.7 cm) (-5 in) to a magnet.

A reversible heavy duty hammermill with a capacity of 27.7 mt/hr (30 ton/hr) will be used to reduce the oversized fraction. A heavy steel hood is used to confine heavy materials ballistically ejected by the hammers. A steel chain curtain would be used over the entrance of the conveyor belt to prevent damaging ejections. The grate at the bottom of the shredder would have 12.7 cm (5 in) openings to limit the size of the exiting refuse. The bulk density of the shredded refuse is between 80.1 and 320.4 kg/m^3 (5 and 20 lb/ft^3) with an average of about 160.2 kg/m^3 (10 lb/ft^3). The shredded refuse is discharged onto a vibrating pan conveyor, which uniformly feeds the refuse to a belt conveyor going to the magnetic separator.

Two drum magnets, 1.2m dia x 2.1m wide (4ft x 7ft) were selected for ferrous metal recovery. The belts feeding the refuse are positioned about 25.4 cm (10 in) below the drum magnets, and a belt speed of 33.5 to 47.2 m/min (110 to 155 ft/min) is required to maintain a bed depth of about 3.8 cm (1-1/2 in). The recovered ferrous is conveyed to a third drum magnet which serves as a cleaning magnet to provide a cleaner ferrous fraction for recovery. An aspiration system can be incorporated with the drum magnet to pull off more of the light nonferrous fraction. The ferrous fraction with a density of 560.7 kg/m^3 (35 lb/ft^3) can be compacted to about 1201.5 kg/m^3 (75 lb/ft^3)

for transfer to a trailer or rail car for shipping to a ferrous processor. For ferrous compaction, a mini mill (a small vertical hammer mill) has been selected. The compacted ferrous will be conveyed to a dispatch area for loading onto a trailer car adjacent to the building. The nonferrous fraction is conveyed to an air classifier for further processing.

The nonferrous material from the unshredded refuse processing line (12.7 cm) 5 in) is conveyed to a trommel with 1.3 cm (1/2 in) circular openings for processing to remove the fine fraction. The fine fraction (1.3 cm) (+1/2 in) is conveyed to the pit feeding the incinerator. The 1.3 cm (+1/2 in) nonferrous fraction from the trommel goes to a surge bin feeding an air classifier. The nonferrous shredded refuse and the nonferrous fraction from the cleaning magnet are also conveyed to a surge hopper for feeding to a second air classifier.

At the air classifier the light, predominantly organic fraction is separated from the heavy fraction by an upward air column. Each classifier has a capacity to process 22.7 mt/hr (25 ton/hr). The heavies dropping to the bottom of the air classifier, are conveyed to the pit which feeds the incinerator. The light fraction is carried pneumatically to a cyclone for deairing and transfer to the surge hopper feeding a dryer.

Two rotary dryers each with a design capacity of 31.7 mt/hr (35 ton/hr) will be used to remove about 82% of the moisture in the light fraction. These dryers will be indirectly heated to about 176.7°C (350°F) by the combustion gases from the incinerator. From the rotary dryer the dried and heated (148.9°C)(300°F) refuse will be dropped into the hopper to the rotary reactor. The evaporated moisture is vented from the dryer through a filter to the atmosphere. An alternative option is to condense the heated water vapor with the HCl and air mixture used in the reactor. There is considerable heat in the water vapor and its utilization would raise the temperature of the reactor gas and improve the energy efficiency of the plant. The condensed water can be treated and discharged into the sewer system.

Two rotary reactors with a capacity of 27.2 mt/hr (30 ton/hr) will be used for embrittling the dried light fraction of the refuse. The units will operate at about 148.9°C (300°F). The heated and dried light fraction will be tumbled through the reactor in a flowing atmosphere of air and gaseous HCl. At the base of the rotary reactor, the 50/50 gas mixture will be extracted from the top of the cylinder and the treated refuse from the bottom of the cylinder. The concentration level of HCl in the reactor will be maintained as constant as possible. During the reaction process the treated refuse adsorbs some of the HCl gas. Laboratory data indicated that the cellulose waste adsorbs about 2.4% of its weight in HCl during the process. Therefore, 473.5 mt (522 ton) of refuse can be expected to adsorb about 11.4 mt (12.6 ton) of HCl gas. However, by careful processing it may be possible to reduce the amount of HCl adsorbed by the cellulose waste. Preliminary study indicates that the HCl adsorption can be limited to about 1% of the weight of the cellulose waste. The reactant gases will be pulled through a filter and moisture trap then mixed with make-up gases and reheated for reuse. The embrittled light fraction will be conveyed to a ball mill for further processing. A caustic scrubber unit would be available to treat the reactant gases if they cannot be recycled.

Two ball mills with 27.2 mt/hr (30 ton/hr) capacity will be used to reduce the embrittled light fraction to a powder. As the material is reduced in size, it flows toward the exit end of the mill. Under the mill is a rotary disc screen to remove the oversized plastics and other organics which are not pulverized. The rotary disc screens will also have the capacity to process 27 mt/hr (30 ton/hr). The oversized material is conveyed to the incinerator pit and the powder is transported to an air lock feeder for pneumatic conveyance to a storage bin. About 399 mt (440 ton) of powdered fuel will be produced per day. A cyclone separator is mounted on the storage bin to deair the powder. From the storage bin the powdered fuel will be transported to the fuel customer. Trucks will be loaded from the base of the storage bin.

The heavy fraction from the air classifier, the fines from the 1.3 cm (1/2 in) trommel and the oversized from the rotary disc screen will be conveyed to the incinerator pit. About 342.7 mt (378 ton) of refuse will be transported to the incinerator pit for combustion. The incinerator pit, 7.6m x 22.9 x 5.6m (25ft x 75ft x 25ft) will have sufficient capacity to store one day's load, 435.4 mt (480 ton). An overhead crane will transport the refuse from the pit to the incinerator feed hopper. The incinerator will be a conventional moving grate unit operated 24 hr/day with a capacity of 18.1 mt/hr (20-ton/hr). During the 20 hr that the processing lines are in operation, the incinerator will process about 15.6 mt/hr 17.2 ton/hr). During the 4 hr that the process lines are down the incinerators will process about 7.8 mt/hr (8.6 ton/hr). The combustion gases from the incinerator will be piped to the two rotary dryers and from the dryers to the electrostatic precipitators. During the 4 hr down period the combustion gases will be piped directly to the precipitators. A wet scrubber unit is incorporated for quenching the exhaust gases prior to transporting them to the electrostatic precipitator when they are not used in the dryer. Because the gas temperature cannot exceed 315.6°C (600°F) at the precipitator unit, water from the scrubber unit and from the bottom ash quench will be treated and disposed of into the main sewer line. The bottom ash from the incinerator and fly ash from the precipitator will be conveyed to a truck for delivery to the landfill.

In addition to the processing equipment, considerable auxiliary equipment and support facilities are required for the proposed plant. A waste water treatment system is required to treat the drainage water from washing down the tipping floor and process floor and the quench water from the incinerator. This system would remove the scum and settleable solids prior to pumping the water into a main sewer line for further treatment at a municipal facility. An overhead traveling bridge crane is required for maintenance on the shredder and other processing equipment. An electrical substation is also needed to meet the electrical requirements of the proposed plant. The substation would be located adjacent to the processing plant.

A dust control system is another major support facility required by the plant. Air from the dust collection hoods over the selected processing equipment, such as the shredder and other high dust areas like the tipping floor as well as the air from the cyclones have to be treated before it can be released to the atmosphere. Two bag houses and two afterburner units will be required to remove the particulate matter and odors from the plant air before it can be released. These units will be located on the roof of the processing plant. Fire protection and explosion protection units for the processing plant will also be required. These items will be discussed in greater detail in the section on environmental, health, and safety requirements.

Other items of auxiliary equipment also required for the proposed facility include a house air supply, a TV monitoring system, a fuel supply for rolling stock and a heating, ventilating, and air conditioning system.

Plant Contingency Plans

As stated, the proposed processing plant is designed to process 907 mt (1000 ton) of refuse a day. However, it is anticipated that the plant will not be able to operate at full capacity through the year. An 85% on-line availability is assumed for the proposed facility. When the plant is down completely, the raw refuse would be sent directly to a nearby landfill. In addition it is recognized that the quantity of refuse generated is subject to considerable fluctuations due to seasonal variations as well as daily variations. Daily fluctuations can be managed by maintaining limited storage of the refuse to smooth out peaks and valleys in the delivery cycle. Limited quantities of overage due to seasonal changes can be managed by burning increased loads in the incinerator unit. One wall of the incinerator pit fronts on the tipping floor to permit the front end loaders to push part of the refuse into the pit. Large amounts of overage due to seasonal highs would have to be taken to the landfill.

In the proposed facility the processing lines would be closed 4 hr/day for maintenance functions. An aggressive program of daily preventive maintenance should minimize unscheduled down time. However, it is recognized that some unanticipated equipment breakdowns will occur. Two processing lines receive the refuse and separate it into two fractions: +12.7 cm (+5 in) and -12.7 cm (-5 in). Each fraction is then processed on a separate line. If any of the equipment in either line breaks down, it is possible to continue the processing of the other fraction. The refuse from the processing line that is out of order would be passed directly to the incinerator pit. This would be accomplished by bringing in a portable conveyor unit and attaching it to the opposite end of either the 12.7 cm (+5 in) or the 12.7 cm (-5 in) processing line at the trommels. The conveyor would carry the refuse back to the tipping floor for a front end loader to move it to the incinerator pit.

Health, Safety, and Environmental Protection Considerations

This proposed resource plant will conform to all OSHA and EPA regulations. All pit areas will be properly railed and all catwalks and ladders will be enclosed. A fire control water sprinkler system is proposed for all of the buildings. In addition, halogenated hydrocarbon explosion suppression systems are proposed for the primary shredders. A similar halogenated hydrocarbon system is recommended for the control tower and motor control centers. Carbon dioxide fire suppression units are recommended for the refuse conveyor lines, in the trommels, in the air classification system, in the ball mills and screening units, cyclones, dust collection units, and in the storage bins. This system should provide total plant fire and explosion protection.

Recovery of powdered fuel and ferrous metal results in a reduction of solid waste for disposal and the associated environmental problems. However, processing, use and disposal of the products from this proposed facility could result in other types of environmental pollution problems. Waste to energy conversion facilities and the products generated can contribute to land, water, and air pollution. The potential pollution problem and associated control technologies for an embrittlement processing facilities have been considered and the areas of major concern are discussed in the following paragraphs.

Dust and gas emissions from incineration are two of the potential pollution problems which have been identified for the proposed process. Dust emission is a problem that plagues most phases of solid waste processing. Shredding, air classification and screening are major sources of dust emission. Bacteria and virus emissions are closely associated with dust since both generally reside on the surface of the dust particles. Effective dust control for the processing requirements of the proposed facility does not appear to be a problem. Care mustbe taken to enclose all processing equipment and conveyors. In addition, effective exhaust systems must be utilized at the processing equipment and for the plant in general. Fabric filtration units (baghouses) can be readily employed for cleaning the exhaust gases, since the gas is at ambient temperature and the dust is not very abrasive. Pilot studies demonstrated that 99.9% particulate removal efficiencies can be obtained with the use of fabric filters.

Odors from the putrefaction of the food wastes can be picked up by the fluidizing air. Afterburner combustion units are proposed for the exit end of the dust collection system for controlling odors in the exhaust air. Noise control systems do not appear to be required for any of the processing areas, although ear protection is recommended for workers in the shredding area. If the noise from the hammermills does prove to be excessive after start-up, soundproofing paneling can be installed. Hammermill manufacturers do not feel that soundproofing is necessary as part of the installation.

The other cause of air pollution is the exhaust gases from incineration of the heavy and fine fractions which provide the heat source for embrittlement. The uncontrolled emissions from this process should be similar to those reported for most incinerator operations: particulates, HCl, SO_2, NO_x, CO, and unburned hydrocarbons. CO, NO_x, SO_2, and unbruned hydrocarbons do not appear to be a problem nor are any special controls anticipated for these pollutants. HCl removal can be achieved with a scrubber unit; however, appropriate materials selection in the design are necessary to inhibit acid corrosion. Particulate control would probably require an electrostatic precipitator. In addition, since up to 30% of the particulates could be less than 1 μm, the use of a fabric filter system may also be required. Disposal of the fly ash collected is also of concern due to the presence of trace elements (Cl, Pb, Cu, Zn, etc.) found in the fly ash.

The proposed facility for producing a powdered fuel relies primarily on dry processing. The only water required is for quenching the incinerator residue and washing down processing equipment. This water picks up a considerable amount of contaminants, organics, trace metals, acids, etc., and will require preliminary treatment before it can be sent to the waste water facility.

The residue from the proposed facility will come from the incineration process and is relatively inert. The captured fly ash and quenched bottom ash will contain a small amount of unburned organics (2.5%) and some trace elements (Be, Hg, Cl, Pb, etc.) requiring proper sanitary landfill procedures for its disposal.

The powdered fuel obtained by the embrittlement process can cause environmental problems in its use. Combustion of this powdered fuel will produce air pollutants (particulates, trace metals, and gaseous emissions) similar to those described for the incineration of the heavies and fine fraction. Of particular concern are the fine particulates, trace metals and acid vapors. Similar precautions to those described for incineration will have to be taken to control these pollutants.

A problem with the powdered fuel which should also be addressed, although it is not usually covered under environmental concerns, is the explosive potential of the powdered fuel. Fine powders can readily detonate and great care must be exercised in handling and storage of the powdered fuel. It has been reported that several explosions were experienced by A.D. Little and CEA in their work with powdered fuels. It is estimated that the explosive power of the powdered cellulose was equivalent to half that attributed to powdered grain (28). The standard safety practices established for grain should be followed in the handling of powdered fuels.

Another approach to handling the powdered fuel would be to suspend the treated light fraction in a light fuel oil. Grinding and storage of the treated organics in a light fuel oil will inhibit explosions and could facilitate introduction of the powder into the combustion system of a furnace or boiler (29).

ECONOMIC ANALYSIS

An economic analysis was developed for a plant designed to convert 907 mt/day (1000 ton/day) of municipal refuse into a powdered fuel. The plant is based on the flow plan developed in Figure 20. The plant is to be staffed to receive refuse 16 hr/day for 365 days a year. The refuse will be processed for 20 hr/day and the remaining 4 hr would be used for equipment maintenance and house cleaning chores. It has been assumed that a landfill is within 5 miles to serve as a backup to the facility. On an annual basis the facility will process 281,180 mt (310,000 ton) (1000 x 365 x 0.85) assuming an on-line availability of 85%. The analysis that was used followed the format published in EPA document SW-157-6 (30). The data provided are based on 1978 dollars for a site in the East North Central United States. Where data were not available, the guidelines provided in SW-157.6 were used to estimate line item costs. A summary of the capital costs, annual operating and maintenance costs and required revenues is discussed in the following paragraphs. The basis for the data used and the detailed calculations are presented in Appendix A.

A summary of the estimated capital costs for the proposed facility is presented in Table 26. The capital cost is estimated to be $30,319,000. The total interest for revenue bonds on a loan calculated at 8% is $30,585,807 over 20 years. This results in a total cost of $60,904,807 or $3,045,240 annually. The estimated capital cost per ton is $10.84/mt ($9.83/ton).

A summary of the estimated annual operating and maintenance (O&M) costs are presented in Table 27. The total annual O&M cost is estimated to be $7,980,000. This results in an O&M cost per ton of $28.31/mt ($25.51/ton).

The estimated total cost per ton which is the sum of the O&M and the capital cost is $38.96/mt ($35.34/ton). To cover these costs, revenues are anticipated from a tipping fee for waste disposal and the sale of recovered metals and the powdered fuel. A summary of the potential revenue sources required is presented in Table 29. As shown in Table 28, the powdered fuel has to have a market value of $63.46/mt ($57.56/ton) or $0.064/kg ($0.029/lb) in order for the process to break even. With a heating value of about 16,281 kg (7000 BTUs/lb) the powdered fuel would cost $3.89/million KJ ($4.10/million BTU).

Proposed Future Work

Laboratory studies at UDRI have demonstrated that a number of treatments can be used for the embrittlement of cellulose wastes to produce a powdered fuel (P-RDF). Although the process variables have been determined and an engineering design and economic analysis have been established for the production of a P-RDF, there is a need for further research studies. A number of studies to better characterize the P-RDF as a fuel or fuel component are needed. In addition, studies to extend the utilization of embrittlement in resource recovery processes are also needed.

A compilation of the tasks which should be initiated would include:

(a) Combustion analysis of P-RDF fuel.
(b) Oil/P-RDF slurry development.
(c) Embrittlement studies on unprocessed raw refuse.
(d) Embrittlement studies on wood product and crop wastes.
(e) Investigation of partial embrittlement techniques for preparing RDF flakes.

TABLE 26. ESTIMATED CAPITAL COSTS

Item	Amount
Land	$ 967,000
Site Preparation	339,000
Construction	4,856,000
Equipment and Installation	9,272,000
Auxiliary Equipment and Facilities	6,179,000
Subtotal	$21,613,000
Engineering and Design	1,297,000
New Subtotal	$22,910,000
Contingencies	2,291,000
Financing and Legal	505,000
Start-up and Working Capital	4,613,000
Total Initial Capital Investment	$30,319,000
Estimated useful life of facility (years)	20 years
Total interest to be paid	$30,585,807
Total capital cost	$60,904,807
Average annual capital cost	$ 3,045,240
Annual throughput (tons)	281,180 mt (310,000 ton)
Capital cost per ton	$10.84/mt ($9.83/ton)

TABLE 27. ESTIMATED ANNUAL OPERATING AND MAINTENANCE COSTS

Item	Amount
Salaries and Benefits	$1,815,000
Fuel	70,000
Electricity	1,000,000
Water and Sewer	45,000
Maintenance	932,000
Replacement Equipment (straight line depreciation)	2,422,000
Residue Removal	314,000
Materials and Supplies	904,000
Taxes	190,000
Insurance	126,000
General and Administrative Costs	90,000
Total Annual O&M Costs	$7,908,000
Operating and Maintenance Cost/ton	$28.13/mt ($25.51/ton)

TABLE 28. POTENTIAL REVENUE SOURCES

Source	Dollars/ton refuse processed
Tipping Fee	$ 9.37/mt (8.50/ton)
Ferrous Metal	1.65/mt (1.50/ton)
Powdered Fuel $0.064/kg ($0.029/lb)	27.93/mt (25.34/ton)
Total Required Revenue	$38.96/mt (35.34/ton)

(f) Reevaluation of the economics for the embrittlement processes.

Although P-RDF has been characterized, performance in burn tests has not been well established. Therefore, combustion studies of the powdered fuel prepared from the embrittlement of RDF are proposed for future study in a test unit with a burner for pulverized coal. Another area of major interest is the suspension of the P-RDF in an oil. The handling and shipment of a powdered fuel to its point of use presents some problems--a major one being safety hazards arising from the potential explosion characteristics of a finely powdered material. A possible solution to this problem is storing, transporting, and burning the powdered fuel in an oil slurry. The techniques for powder suspension can be initially based on the work done in developing mixtures of powdered coal in oil. Once an effective P-RDF/oil slurry is developed, mixtures of 10, 25, and 50 percent powder/oil slurries can be prepared for combustion tests. It is expected that an air atomizing burner unit would be used for the proposed combustion tests.

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APPENDIX A

BACKGROUND FOR ECONOMIC ANALYSIS[+]

CAPITAL COSTS

1. Land requirements

   a) Required acreage for plant;
   30 acres @ \$12,500/acre = \$375,000

   b) Required acreage for landfill;
   process residue: 142 TPD x 365 = 51,830 TPY
   raw refuse: (1000 x 365) - [(1000 x 365).85] =
   54,750 TPY

Total waste for landfill 106,580 TPY. Assuming 1000 lbs/yd^3, gives 213,160 yd^3/yr. Allowing 25% for fill gives 266,450 yd^3/yr. This converts to 7,194,150 ft^3/yr. Assuming two tiers at 20 ft/tier for the landfill results in a requirement of 179,854 ft^2/yr for 20 years or a total of 3,597,080 ft^2. In addition allowing for a 10% buffer zone increases the requirement to 3,956,788 ft^2 which converts to 91 acres. At an estimated cost of \$6,500/acre the cost for landfill would be \$592,755. Total land costs are estimated to be \$967,755.

2. Site preparation

Allowing 35% of land costs for site preparation gives .35 x \$966,500 = \$338,275.

3. Construction costs

Average construction costs for the North East Central states was given at \$42/ft^2 by a local A&E firm in the field.

The proposed plant would occupy a building complex of 114,900 ft^2; therefore, \$42 x 114,900 = \$4,825,800. In addition about \$30,000 is required for the scale house. Total construction costs would be \$4,855,800.

[+] All calculations are given in engineering units (see conversion chart, page A-10).

4. Equipment and installation

Based on manufacturer's data a complete list of the required equipment for the proposed plant was developed. This list itemizes all equipment costs and installation costs (see Table A-1). Total cost would be $9,272,000.

TABLE A-1. EQUIPMENT AND INSTALLATION COST

	Equipment Description	Equipment cost	Installation cost	Total cost
1.	2-Trommel (5")	$107,000	$ 28,900	$ 135,900
2.	Coarse shredder (5" grate OPN)	81,800	38,400	120,200
3.	Magnetic separator #1	23,525	11,475	35,000
4.	Magnetic separator #2	23,525	11,475	35,000
5.	Cleaning magnet	17,823	8,705	26,528
6.	Trommel (1/2" OPN)	41,658	11,248	52,906
7.	2-Air classifiers with cyclones	403,000	166,800	569,800
8.	Metal compactor	100,000	51,500	151,500
9.	2-Rotary dryers	700,000	350,000	1,050,000
10.	2-Rotary reactors	700,000	350,000	1,050,000
11.	Ball mill	130,000	65,000	195,000
12.	2-Rotary disc screens	40,000	20,000	60,000
13.	Incinerator system*	--	--	5,000,000
14.	Heat exchanger	20,000	10,000	30,000
15.	Acid scrubber	10,000	5,000	15,000
16.	Caustic tank	6,376	3,624	10,000
17.	Powder storage bin	67,500	45,350	112,850
18.	Pneumatic powder conveying system	26,000	8,000	34,000
19.	27-Conveyors	--	--	588,400
	TOTAL			$9,272,084

*Incinerator system includes the grate unit, wet scrubber, electrostatic precipitator, pit and crane.

5. Auxiliary equipment and facilities

A similar compilation of all required auxiliary equipment and facilities has also been compiled (see Table A-2). Total cost is $6,179,000.

TABLE A-2. PLANT FACILITIES AND AUXILIARY EQUIPMENT COST

	Equipment description	Total cost
1.	2 Scales	$ 52,000
2.	2 Fork trucks	24,000
3.	1 Pickup truck	4,000
4.	3 Frontend loaders	128,500
5.	Explosion protection system	88,500
6.	Miscellaneous conveyors	500,000
7.	2 Bag house systems	1,120,000
8.	Electrical substation and motor controls	1,191,000
9.	HCL system	74,000
10.	Small tools	62,000
11.	T.V. security system	47,000
12.	Power sweeper	24,000
13.	Office furniture	17,000
14.	Bathroom fixtures and accessories	4,000
15.	Sump pumps	2,000
16.	Lab equipment	10,000
17.	Fire protection	206,000
18.	Heating, ventilation and air conditioning system	125,000
19.	Wastewater treatment system	1,000,000
20.	Overhead crane	1,500,000
	TOTAL	$6,179,000

6. Engineering and design

It is assumed that the engineering and design costs are based on the average engineering and design assignment rather than a first of a kind facility. A conventional 6% fee was used for A&E services. .06 x $21,613,000 = $1,296,780.

7. Contingencies

A value of 10% has been allowed for contingencies. $22,910,000 x .1 = $2,291,000. (The new subtotal for items 1-7 = $25,201,000.)

8. Financing and legal fees

Referencing SW-157.6 a value of 2% of the capital costs should be used for the cost of a bond counsel, legal fees, financial management consultants, etc. to cover financing the loan for the facility. Therefore, $25,201,000 x .02 = $504,020.

9. Start-up and working capital

Seven months payroll (4 mo start-up and 3 mo working capital) has been selected for this item. (Table 28 in the text shows the annual O&M costs.) Therefore, $7,908,000 x 7/12 = $4,613,000. Total initial capital investment rounded to the nearest $1,000 is $30,319,000.

10. Interest to be paid

For a 20 yr loan the monthly payment (per $1,000 loan) at 8% interest is reported in the tables to be $8.37. Per yr this would be $100.44 and for 20 yrs would be $2008.80. For a loan of $30,319,000, the total payment would be: $2008.80 x 30319 = 60,904,807 - 30,319,000 = $30,585,807.

11. Total capital cost - $60,904,807.

12. Average annual capital cost - $60,904,807÷20 = $3,045,240.

13. Capital cost per ton - $3,045,240÷310,000 = $9.83.

OPERATING AND MAINTENANCE COSTS

14. Salaries and benefits

A complete list of all personnel required to operate the proposed plant has been developed. Job descriptions for all positions have also been prepared. This information has been used to develop yearly manpower costs. A summary of yearly manpower costs is presented in Table A-3.

TABLE A-3. ANNUAL MANPOWER COSTS

Position	Annual cost for each position	Number required	Total cost
Weighmaster	$16,117.23	3	$ 48,351.69
Front-end loader operator	18,488.30	8	147,906.40
Control tower operator	18,488.30	8	147,906.40
Process operator	18,488.30	8	147,906.40
Assistant process operator	16,592.12	12	199,105.44
Incinerator operator	18,488.30	4	73,953.20
Assistant incinerator operator	16,592.12	8	132,736.96
Maintenance man	21,245.88	12	254,950.56
Maintenance helper	18,849.13	12	226,189.56
Utility man I	18,849.13	4	75,396.52
Utility man II	15,722.91	3	47,168.73
Receiving area attendant	13,069.16	1	13,069.16
Janitor	14,997.65	1	14,997.65
Crane operator	18,488.30	4	73,953.20
Foreman	24,522.02	4	98,088.08
Plant manager	32,955.40	1	32,955.40
Assistant plant manager	29,341.30	1	29,341.30
Billing clerk	11,577.31	1	11,577.31
Accounting clerk	13,277.66	1	13,277.66
Secretary	11,577.31	1	11,577.31
Quality control technician	14,978.02	1	14,978.02
TOTAL	---	98	$1,815,386.50

Yearly manpower costs - $1,815,386.80.

The wage rate used in this analysis is based on the projected rates in effect during 1978 in the northeast central United States. A proposed work schedule is summarized in Table A-4. In order to maintain 24 hr staffing of the foreman, incinerator operator and utility man positions, a 4-man crew could be scheduled to work 6 days, be off 2 and then rotate shifts. This scheduling procedure necessitates a planned overtime of 50

TABLE A-4. PROPOSED WORK SCHEDULE

Day	Monday			Tuesday			Wednesday			Thursday			Friday			Saturday			Sunday		
Shift	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Weighmaster	1	1		1	1		1	1		1	1		1	1		1	1		1	1	
Front end loader operator	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Control tower operator	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Process operator	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Assistant process operator	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Incinerator operator	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Assistant incinerator operator	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Maintenance man	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Maintenance helper	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Utility man I	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Utility man II	1	1		1	1		1	1		1	1		1	1		1	1		1	1	
Receiving area attendant	1			1			1			1			1								
Janitor			1			1			1			1			1						
Crane operator	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Foreman	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Plant manager	1			1			1			1			1								
Assistant plant manager	1			1			1			1			1								
Billing clerk	1			1			1			1			1								
Accounting clerk	1			1			1			1			1								
Secretary	1			1			1			1			1								
Quality control technician	1			1			1			1			1								
Total	30	23	22	30	23	22	30	23	22	30	23	22	30	23	22	23	23	22	23	23	22

shifts a year per crew. The men on each of these crews will have to work an average of 12.5 overtime shifts.

The wage rate for each position is multiplied by 2080 hr in order to obtain the annual cost for that position. This rate includes vacation and sick leave pay, company-paid medical and dental insurance, disability income and long-term disability insurance, a company-paid retirement plan, and normal state and federal payroll taxes. A shift differential of \$.12 for the second shift and \$.18 for third shift has also been included and the average value for the differential is added to the wage schedule.

15. Fuel

Estimated fuel costs for the 2 front-end loaders are \$5.20/hr x 16 hr x 2 units = \$160/day x 365 days = \$58,400 or rounded off ≈ \$60,000. Estimated cost for other plant vehicles is 300 gal/wk @ \$.60/gal = \$180/wk x 52 ≈ \$10,000. Total cost; \$70,000.

16. Electricity

Total estimated power requirements for the plant is 700 x 10^6 BTU/day. This translated to 700 x 10^6/3 x 1/3412.2 = 68,382 KWh. Using an electric rate of \$.04/KWh gives a cost of 68,382 x 365 x .04 = \$998,378.40.

17. Water and sewer

Based on a flow requirement of 175 gal/min the combined sewer and water rate was calculated to be \$44,496/yr.

18. Maintenance

Maintenance material and outside service costs are estimated at 5% of the total installed cost of all equipment. In addition, 1% of the construction cost for all buildings is estimated for additional building maintenance costs. Additional maintenance costs can also be expected for the shredder and rolling stock.

extra shredder maintenance cost	\$ 96,496
rolling stock maintenance cost	14,483
equipment \$13,561,000 x .05	678,050
buildings \$4,855,800 x .01	48,558
	\$837,587

19. Replacement equipment

A straight line depreciation formula was used for replacement of equipment:

Buildings 20 yr = $4,855,800 ÷ 20	$ 242,790
Rolling stock - 3 yr = $156,500 ÷ 3	52,167
Shredder - 10 yr = $120,200 ÷ 10	12,020
Scale - 10 yr = $52,000 ÷ 10	5,200
Electrical equipment - 10 yr = $1,191,000 ÷ 10	119,100
All other equipment - 7 yr = $12,088,100 ÷ 7	1,726,871
	$2,158,148

20. Residue removal costs

142 TPD
x 365

51,830 ≈ 52,000 TPY

Land disposal fee @ $4.50/ton	$234,000
Transportation	80,000
	$314,000

21. Taxes

Estimated taxes @ 0.75% of the capital cost of the facility are $22,999,000 x .0071 = $172,492.

22. Insurance

Estimated insurance @ 0.05% of the capital cost of the facility is $22,999,000 x .005 = $114,995.

23. Materials and supplies

General supplies estimated @ $2000/mo	$ 24,000
Anhydrous HCl quoted at $225/ton delivered is $225/ton x 12.6 tons/day x 310 days =	880,000
	$904,000

24. Annual general and administrative costs

Postage and office supplies	$ 1,500
Janitorial services	2,000
Telephone	3,500
Monthly accounting	4,500
Year end audit	3,800
Laboratory supplies	3,000
Landscaping	3,500

24. Annual general and administrative costs (Continued)

Travel	7,500
Public relations	7,200
Employee services	7,200
Subscriptions and misc.	7,200
Security services	38,000
	$89,000

25. O&M Recount

	$1,815,000
	70,000
	1,000,000
	45,000
	932,000
	2,422,000
	314,000
	904,000
	126,000
	190,000
	90,000
	$7,908,000

Per ton cost

$$\frac{\$7,908,000}{310,000 \text{ tons}} = \$25.51$$

REVENUES

26. Tipping fee

Waste disposal costs are subject to considerable variation. Using a range from $4.50 to $12.50 per ton (landfill vs. incineration) an average value of $8.50 was selected.

27. Ferrous metal sale

66.5 tons are recovered/day with an average market value of $22.50/ton. This gives a revenue of .0665 x $22.5 = $1.50.

28. Powdered fuel sale

Sale of the fuel has to cover the remaining per ton processing costs of the facility.

Total processing cost - $35.34/ton
Revenues - $8.50 + 1.50 = $10.00

Required cost for powdered fuel is $35.34 - $10.00 = $25.34/ton. The fuel recovered is 44.02% of the raw refuse delivered; therefore, $25.34 ÷ .4402 = $57.56/ton. The cost/lb is $57.56 ÷ 2000 = $0.029/lb. The heat content of the powder was measured at 7000 BTU/lb which gives a cost per 10^6 BTU of $0.029/7000 = $4.10.